An estimation of emissions from domestic biofuel combustion over southern Africa

By

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Declaration

I declare that this dissertation is my own unaided work. It is being submitted for the degree of Master of Science in the University of the Witwatersrand, Johannesburg. It is not been submitted before for any degree or examination in any other degree.

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_____________________ day of _______________________ 2006.

Abstract

Combustion of fuel wood, charcoal and non-woody biofuels is a daily practice for about half of the world's population. Combustion of biofuel is a major source of trace gases, with domestic biomass burning contributing about 17% carbon dioxide (CO_2), 13% carbon monoxide (CO) and 6% nitrous oxide (N_2O) to the global budget. In Africa, where there is a growing population, domestic biofuel emissions are a particularly important source of trace gases. The most important source of biomass fuels in Africa is wood fuel (wood and charcoal), crop residues and animal dung. In this project, the amount of domestic biofuel used in rural households across southern Africa was measured daily over a nine month period. This data was used to estimate the trace gas production from domestic fires throughout Southern Africa. Results indicate that RSA contributed the most trace gases to the regional budget (9.12 Tg C yr^{-1} of CO_2, 0.89 Tg C yr^{-1} of CO, 10.77 Gg N yr^{-1} of NO and 30.25 Gg C yr^{-1} of CH_4) and Botswana the least (0.25 Tg yr^{-1} of CO_2, 0.02 Tg yr^{-1} of CO, 0.29 Gg yr^{-1} of NO and 0.83 Gg yr^{-1} of CH_4). Fuel wood is the dominant fuel type used in all southern African countries, whereas charcoal was used in RSA, Mozambique and Zambia and maize residues in Malawi only. CO_2 was the gas emitted in the largest quantities, with fuel wood and charcoal in RSA contributing the most (8.71 Tg yr^{-1} and 0.41 Tg yr^{-1} respectively), while CO_2 from maize residue was highest in Malawi (0.82 Tg yr^{-1}). More trace gases were emitted in the dry season than wet season particularly in Malawi and Mozambique. For the entire region the annual CO_2, CO, NO and CH_4 emissions produced 23.0 Tg C, 2.2 Tg C, 29.4 Gg N and 81.4 Gg C, respectively.

In memory of my father

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List of Abbreviation

BC - Biofuel Consumption

CO_2 - Carbon dioxide

CO - Carbon monoxide

CH_4 - Methane

EF - Emission Factor

g C - Grams of Carbon

Kg- Kilograms

MCF - Moisture Correction Factor

NMHC - Non – methane Hydrocarbon

NO - Nitrogen Oxide

N_2O - Nitrous Oxide

O_3 - Ozone

RSA - Republic of South Africa

Tg C - Terra grams of Carbon

Tg C yr^{-1}- Terra grams of Carbon per year

Chapter 1

Introduction

Trace gases (carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxide (NO), non-methane hydrocarbons (NMHCs)) and aerosols released through biomass burning have a significant influence on climate and biogeochemical cycles (Crutzen and Andreae, 1990; Crutzen *et al.*, 1997; Andreae, 1991). Biomass burning contributes to the greenhouse effect directly through the emission of CH_4 and nitrous oxide (N_2O) and indirectly through the production of tropospheric ozone (O_3) (Lindesay, 1992). CH_4 emitted is sufficiently long-lived to enter the stratosphere and take part in the stratospheric O_3 cycles (Gupta *et al.,* 2001; Dignon and Penner, 1991). CH_4 and NO_x also influence the local and downwind concentrations of the major atmospheric oxidants, namely O_3 and the OH radical (Prasad *et al.,* 2000). NO_x is also a primary pollutant that forms nitric acid, a major contributor to acid wet and dry deposition, as well as being a major limiting nutrient in some soil and ocean ecosystems. Finally, biomass burning emissions can alter the radiation budget of the earth, either by contributing to global warming through the production of aerosols (Prasad *et al.*, 2000).

Combustion of fuel wood, charcoal and non-woody biofuels is a daily practice for about half of the world's population (Crutzen and Andreae, 1990). Biofuel burning provides about 15% of the world's primary energy (Johansson and Lundqvist, 1999; Bhattachayra *et al.,* 2000; Bhattachayra and Salam, 2002), with 13% being used in developing countries and the remaining 2% in developed and/or industrialized countries. Biomass energy plays a vital role in meeting the local energy demand of the developing world, and often accounts for more than 90% of the total rural energy supplies in developing countries (Bhattachayra *et al.,* 2000; Bhattachayra and Salam, 2002; Andrasko *et al*, 1999; Brocard *et al.,* 1996). This is due mainly to the availability of biofuel to many of the world's poor and affordability as a domestic energy source (Karekezi *et al.,* 2004).

Most of the domestic emissions are taking place in developing countries of Asia, Africa and Latin America (table 1.1). An estimate shows that wood fuel contributes 84.2% of the total wood production in the developing countries and 12.3% of the total wood production in the developed countries, hence biomass fuels meet a major fraction of the domestic energy demand in developing countries (Mia *et al.*, 2003). Due to population increases the biofuel use, and thus emissions, has increased over the last century (Houghton, 1991). Fuel wood, charcoal, animal dung and maize residues account for more than 30% of the global sources of atmospheric NO_x and NMHC, about 40 % of CO emissions and about 15% of CH_4 emissions (Lindesay, 2000).

Table 1.1: Emission estimates from domestic biomass combustion for 1993 (Ludwig *et al.,* 2003) and for 1995 (Yevich and Logan, 2003) for regions across the world.

	Emission estimate						
	CO_2 (Tg C yr^{-1})		**CO (Tg C yr^{-1})**		**NO (Tg N yr^{-1})**		**CH_4 (Tg C yr^{-1})**
Region	**Ludwig *et al.***	**Yevich and Logan**	**Ludwig *et al.***	**Yevich and Logan**	**Ludwig *et al.***	**Yevich and Logan**	**Yevich and Logan**
Africa	296	527	28	28	0.50	0.40	1.66
Asia	886	1808	84	102	1.51	1.41	5.93
Latin America	110	353	10	20	0.19	0.20	1.16
Oceania	3		0		0.00		
North America	114		11		0.19		
Europe	40		4		0.07		
Former USSR	46		4		0.08		
World total	1495	2688	141	150	2.54	2.01	8.75

In Africa burning is used in certain farming practices to clear land and also for domestic use, such as cooking and space heating (Kgathi, 1997). The production of charcoal is also a major source of biofuel emissions in some parts of Africa. Africa is marked by contrast in geoclimatic and vegetation conditions, from the Northern drylands through the large desert and savanna zones with fuel wood deficits, to the forest zones with fuel wood surplus (Yevich and Logan, 2003). Africa is currently a continent where domestic biomass burning is greater than in Latin America (table 1.1). Biomass energy will continue to be a dominant source of domestic energy generation in Africa, and combined with population growth biofuel use is likely to increase. Africa could therefore be a major contributor to atmospheric emissions due to the high biofuel usage.

There is a growing concern about the adverse impacts that domestic biomass (especially wood fuel) burning places on the environment as well as on the health of people in the developing world (Marufu *et al.*, 1997). Reliance on biomass energy (especially in the form of charcoal) contributes to land degradation and deforestation in countries where charcoal, sourced from natural forest, is widely used (Karekezi *et al.,* 2004). In terms of health, fire wood is generally burnt under inefficient conditions in poorly ventilated areas that cause an increase in the amount of health damaging air pollutants (Brocard *et al.,* 1996). When combustion of biomass fuels is complete the only products are CO_2 and water, which are not harmful, whereas incomplete combustion releases health damaging pollutants and greenhouse gases such as CH_4, CO, NO_x and other organic compounds (Bhattachayra *et al.*, 2000). The adverse effects on health associated with indoor pollution from biomass use include respiratory diseases, chronic lungs and cancer (Kgathi, 1997).

1.1 Problem statement

Air pollution is a major problem over southern Africa. Trace gases such as CO_2, CO, CH_4 and N_2O produced from biomass burning are equivalent to anthropogenic emissions (Yevich and Logan, 2003). Emissions from savannas are fairly well understood, however, contribution of emissions from domestic biomass combustion to global trace gas budgets is still unclear. Furthermore, domestic biomass burning for energy generation constitutes a continuous input of trace compounds into the atmosphere, unlike vegetation fires that are a seasonal phenomenon (Ludwig *et al.*, 2003). As such there is a need to calculate more accurate emission estimates of trace gases from biofuel combustion.

It has been noted that data on biomass energy in Africa is, particularly in the sub-continent, problematic and most of the African countries do not have sufficient, reliable and up to date databases on biomass energy (Karekezi *et al.,* 2004). The scattered and small scale nature of domestic biomass burning is one of the reasons why there is a lack of information. Furthermore, since much of the fuel is obtained by individual gathering and not marketed, adequate statistics on fuel use are not kept.

Consumption rates have been measured in southern Africa before (Marufu *et al.,* 1999) but this data was collected only at one time of the year. Due to seasonal variation, the use of biofuels as a daily activity is expected to vary throughout the year. Seasonal variations on the emissions from domestic biofuel burning have been estimated but have not actually been measured.

In order to obtain accurate annual estimates of emissions from fuel used, the consumption rates need to be measured throughout the year. Part of this project was to collect improved consumption rate data for the southern African region[1], but the main focus of this study is the seasonal variation in emission estimates from domestic biofuel burning in the sub-continent.

Trace gas emissions are expected to increase as a result of increased domestic biofuel combustion. In the early 1980s deforestation due to fuel wood collection and other land use increased in Africa. The demand for fuel wood grew about 3% annually and it led to high wood fuel combustion and demand that result in an increase concentration of trace compounds in the atmosphere (Hao and Ward, 1993). Emissions from domestic fuel use in Africa could still be increasing due to growing populations and could be a significant contributor to global atmospheric chemistry. For this reason it is extremely important that we obtain accurate annual estimates of domestic biofuel emissions. These numbers will also allow for more accurate future projections.

[1] Detailed biofuel data collection and results are given in the MSc report of Tshikalanke R.P.

1.2 Objectives

The specific objectives of this project are to:

1. calculate the trace gas emissions from domestic biofuel combustion in southern African countries;
2. investigate the emissions from different fuel types;
3. investigate the seasonal variation in emissions from biofuel combustion; and
4. compare the emissions of trace gases between different southern African countries.

Chapter 2

Literature review

2.1 Global biomass burning

Over the last decade, it has become increasingly apparent that the trace gas composition of the atmosphere is changing and its environmental consequences are noticeable. One of the causes of this change has been linked to biomass burning, especially since it occurs over extensive areas and appears to be increasing every year. Biomass burning refers to anthropogenic activities associated with savanna burning, slash and burn for agriculture, burning for deforestation purposes and for disposal of agricultural waste, biofuel burning as well as forest wildfires; whereas biofuel burning refers to all burning for purposes of domestic energy generation only (Marufu *et al.,* 2000).

It is evident from table 2.1 that emissions from biofuel burning constitutes between 20 and 50% of the global biomass burning emission budget; and on a global bases it contributes a quarter of the global trace gas emission budget (Gupta *et al.,* 2001). Burning in the tropics is currently receiving special emphasis because it is believed to constitute the largest fraction of global biomass burning. Savanna fires are estimated to contribute about 50 – 67% to tropical biomass fire emissions while fuel wood burning is estimated to contribute about 25 – 33% (Wesley *et al.,* 1996).

Most of the biofuel burning occurs in the developing world. Asia contributes the most to the biofuel burning emissions budget of the developing world, mainly due to China and India accounting for 71% of the Asian total, with Africa as the second largest contributor (table 2.2) (Yevich and Logan, 2003).

Table 2.1: Global emissions of trace gases emitted from various types of biomass burning sources in late 1990s (from Andreae and Merlet, 2001).

Gas	Emission from different biomass sources (Tg yr^{-1})					
	Savanna & Grassland	**Tropical Forest**	**Fuel wood Burning**	**Charcoal Burning**	**Agricultural Residues**	**Total**
CO_2	5096	2101	4187	99	818	12301
CO	206	139	209	11	50	615
CH_4	7.4	9	16.5	0.24	1.5	34.64
NO_x	12.2	2.2	2.9	0.15	1.3	18.75

Table 2.2: Emission estimates from domestic biomass combustion for 1995 (from Yevich and Logan, 2003) for regions across the world.

Region	Emission estimate			
	CO_2 (Tg C yr^{-1})	**CO (Tg C yr^{-1})**	**NO (Tg N yr^{-1})**	**CH_4 (Tg C yr^{-1})**
Africa	527	28	0.40	1.66
Asia	1808	102	1.41	5.93
Latin America	353	20	0.20	1.16

2.2 Biofuel burning in Asia and Latin America

Fuel wood is the dominant biofuel type used in Asia and is the highest contributor of emissions in Nepal and Pakistan, while dung is the highest contributor of emissions in India and agricultural residues in China (table 2.3). In India the use of biomass as domestic biofuel account for about 50% of the total primary energy consumption in the country and the major source of biofuels are wood, crop residues and dung (table 2.3) (Joshi, 1991). Animal dung use increases from south to north of a country, agricultural residue use increases from north to south and fuel wood combustion reaches its highest level in the eastern plateau of Himalayan zones (Yevich and Logan, 2003). Emissions vary across the region depending on the fuel type and associated emission factor. Agricultural residues contribute higher emissions than dung due to high emission factors (Battachayra *et al.,* 2000). China has an abundance of biomass energy resources, hence there is high fire wood combustion, which accounts for the second highest (after India) total national fuel wood consumption.

Due to abundant fuel wood and an increasing population growth the emissions from biofuel burning in Asia are high (Xiaohua and Zhenmin, 2003).

Table 2.3: Emissions from various domestic biofuel types in selected Asian countries between 1991 and 1995 (from Bhattachayra *et al.,* 2000).

Country	Emissions from domestic biofuel combustion, Kilo tones (kt)				
	CO_2	CO	CH_4	NO_x	Total
India (1991)					
Fuel wood	139011	4650	913	83	144658
Agric. Res	43282	860	97	44	44284
Dung	78900	62104	3339	473	144825
Charcoal	2295	53	10	2	2362
Total	*263489*	*67668*	*4360*	*603*	*336130*
China (1993)					
Fuel wood	80594	3264	529.45	90	84479
Agric. Res	153677	6755	345.71	165	160944
Dung	7923	389	60.47	38	8411
Charcoal	217	22	0.70	0.29	240 .7
Total	*242412*	*10431*	*936*	*294*	*254075*
Nepal (1993)					
Fuel wood	11490	538	82	14.1	12125
Agric. Res	3482	208	7.8	3.8	3702.8
Dung	1544	72	11	1.3	1630.8
Charcoal	16	35	0.1	0.05	52.1
Total	*16534*	*855*	*102.3*	*19.3*	*17511*
Pakistan (1991)					
Fuel wood	31141	1261	204	34	32642
Agric. Res	9115	400.7	20	9.8	9546.1
Dung	10538	517.9	80	51	11187.9
Charcoal	369	37.4	1.1	0.4	408
Total	*51164*	*2217*	*306.7*	*96*	*53784*

The energy requirement of Bangladesh is met from different sources such as biomass, electricity, oil, gas and others. The people of rural areas depend mainly on biofuel such as wood, agricultural residues and cow dung for their domestic consumption (Mia *et al.,* 2003). Overall, trees provide 48% of the current rural domestic energy requirement, agricultural residues provide 36% and cow dung provides 13% and the remaining 3% are supplied from peat deposits (Mia *et al.,* 2003).

There is fuel wood deficiency in other Asian countries such as Iraq, Afghanistan and Pakistan and they have open mixed forest grassland and shrub vegetation zones with only a small wood supply available to the large rural population, hence fuel wood consumption is fairly low (0.1 kg per capita per day) (Yevich and Logan, 2003). In these areas agricultural residues are often used as a substitute (Yevich and Logan, 2003). Even though less wood is burnt in these areas trace gas emissions are still important since the emission factor for crop residues is higher than for wood in all gases except for CO.

Throughout Latin America firewood is the primary source of biomass energy. Brazil is the third largest biofuel consumer in the developing world following China and India (table 2.4). The biofuel consumed in Brazil include wood, charcoal and bagasse and represent half of all biofuel utilized in Latin America (Yevich and Logan, 2003). Rural population in many Latin American regions (Mexico, Paraguay, Bolivia, and Peru) relies heavily on fuel wood. Wood fuel (charcoal and fuel wood) accounts for about 10% of urban household (Jamaica, Belize, Surinam) energy use (particularly charcoal) and about 74% of the rural households (Venezuela, Chile, Mexico, Paraquay) energy use. For instance, the highest rate of wood fuel consumption (2.9 kg per capita per day) is in Paraguay that is equivalent to 47 Tg of dry matter (Yevich and Logan, 2003). Hence highest emissions from domestic biofuel combustion are produced from rural households of Latin America with the least emissions from urban areas.

Table 2.4: Domestic biofuel combustion (Tg C) in 1985 for India, China and Brazil (Yevich and Logan, 2003).

	Biofuel		
Country	**Crop residue**	**Dung**	**Wood fuel**
India	35	33	99
China	118	7	119
Brazil	19	-	46
Africa	19	4	159

2.3 Biomass burning in Africa

In tropical Africa vegetation fires such as savanna and forest fires, domestic biofuel burning and agricultural waste burning are a major source of atmospheric pollution (Lacaux *et al.,* 1996; Hao and Ward, 1993). Savannas are the single largest source of biomass burning emissions in Africa (Andreae *et al.,* 1996). For example, in west Africa savanna burning is a larger source of trace gases than biofuel burning (table 2.5), as is the case for southern Africa (see table 2.6 in the next section). The main reason for the high emissions from savanna burning in Africa is because of the seasonal oscillation between a wet season, during which an ample biomass is produced, and a prolonged dry season during which biomass is turned into a flammable material (Andreae *et al.,* 1996). Even though vegetation fires contribute more to trace gas budgets, biofuel burning has the potential to produce much larger quantities, considering the population increase and the fact that biofuel burning results in low combustion efficiencies and high emissions of trace gases (Hao and Ward, 1993; Ludwig *et al.,* 2003).

Table 2.5: Emissions from biofuel in west Africa (Brocard *et al.,* 1996) and savanna burning in west Africa (Menaut *et al.,* 1991).

Trace compound	**Emissions from different biomass sources (Tg yr^{-1})**		
	Charcoal	**Fire wood**	**Savanna**
CO_2	2.7	33	90.6
CO	0.4	2.5	5.6
CH_4	0.01	0.12	0.29

Even though savanna burning is the main source of trace gases from biomass burning, domestic fuel burning still has the potential to be a major contributor. Domestic fuel burning is more constant than biomass burning as there are always people who need to cook food and keep themselves warm, and the number of people is constantly increasing. Vegetation burning is more variable from year to year due to climatic changes. The ratio of emissions from biofuel burning versus vegetation burning thus varies from year to year. For example, in Zimbabwe in 1992 there was a drought and the emissions from vegetation only amounted to 2.0 Tg of CO_2, 0.11 Tg of CO and 8.9 Gg of NO (Ludwig *et al.,* 2003). Comparing this to annual domestic emissions

(4.1 Tg of CO_2, 0.37 Tg CO and 6.0 Gg NO) in 1995 (Ludwig *et al.,* 2003)) it is seen that biofuel burning emissions have the potential to produce as much trace gases as vegetation burning.

About 50% of fuel in Africa is used for cooking, 30% for domestic heating and 20% for various purposes such as pottery (Andreae, 1991). Fuel wood, crop residues and dried animal wastes are burned in large quantities in traditional domestic stoves and cookers for the purposes of space heating and food preparation (Bhattachayra *et al.,* 2000; Bhattachayra and Salam, 2002). In southern Africa more than 90% of households burn biomass on open fires (Marufu *et al.*, 1997; Ludwig *et al.*, 2003; Bhattacharya *et al.,* 2000).

Per capita wood fuel consumption depends on availability and biofuel demand, and it ranges from an estimated low of 0.05 kg per capita per day in Lesotho to upwards of 3.0 kg per capita per day in the eastern highland countries of Kenya, Tanzania, Uganda and Zambia throughout the year (Yevich and Logan, 2003). This would result in low trace gas emissions in southern parts of Africa and high emissions rates in the eastern highlands due to the high fuel wood consumption rates.

Guinea, which has extensive forest cover and abundant fuel wood resources, has the highest fuel wood consumption of 3.2 kg per capita per day over West Africa. Nigeria, Tanzania, Kenya and Zaire use about 50% of the total fuel wood consumption in Africa, which is equivalent to a trace gas production of 138 Tg yr^{-1} (Yevich and Logan, 2003). The Sahel countries such as Chad are sparsely populated with desert and drought, thus they have the lowest fuel wood consumption resulting in low trace gas emissions from domestic biofuel combustion. Other countries such as Madagascar are densely populated and have inhabitants who rapidly deplete wood resources and as a result trace gas production from domestic biofuel burning is fairly high (Yevich and Logan, 2003). The coastal countries of west Africa contain areas of wooded savanna and dense forest, with a sparse to heavy population density. The fuel wood consumption estimates are mostly within the range of 1.3 to 1.7 kg per capita per day (Yevich and Logan, 2003).

In many regions of Africa fuel wood crisis, due maily to population increases, have been noticed and its increasing scarcity is a subject of major concern in Africa (Kgathi, 1997; Delmas *et al.,* 1991). High population growth rates and increasing household fuel demands are associated with rapid increases in trace gas emissions (Kituyi *et al.,* 2001).

2.3.1 Biomass burning in southern Africa

In southern Africa approximately 30% of trace gas emissions are produced from domestic biofuel burning and the remaining percentage is from forest fires and savanna (table 2.6) (Marufu *et al.,* 1999). RSA produces the highest emissions from both biofuel and savanna and Swaziland produced the least. South West Africa contributed low emissions from fuel wood and this is largely due to the low biomass found in the Kalahari Desert in Botswana and Namibia.

Table 2.6: Emissions from savanna burning (Scholes *et al.*, 1996) and biofuel burning (Marufu *et al.*, 1999) in southern Africa for 1989.

Country	Emission estimate					
	CO_2 (Tg yr^{-1})		CO (Tg yr^{-1})		CH_4(Gg yr^{-1})	
	Biofuel	Savanna	Biofuel	Savanna	Biofuel	Savanna
Botswana	0.22	13.2	0.02	0.43	1.11	0.013
Lesotho	0.51	0.4	0.04	0.01	3.52	0.00
Malawi	2.78	7.1	0.28	0.24	17.84	0.007
Mozambique	5.21	25.6	0.47	1.03	26.13	0.033
Namibia	0.56	4.4	0.05	0.13	2.20	0.004
RSA	8.42	11.4	0.76	0.4	37.01	0.015
Swaziland	0.17	0.1	0.02	0.00	0.64	0.00
Zambia	3.77	53.6	0.42	2.50	39.16	0.084
Zimbabwe	4.06	7.2	0.38	0.26	15.68	0.008

More recently Bertschi *et al.* (2003) measured emissions from domestic biofuel burning in Zambia and estimated annual emissions in the year 2000. Results indicated that fuel wood use is increasing by 1% every year compared to other trace gas emissions that were measured in previous years. More fuel wood is used than charcoal in Zambia with wood burning producing 9.8 Tg C yr^{-1} as CO_2 and charcoal producing only 3.3 Tg yr^{-1} of CO_2 (table 2.7). NO_x was emitted in the lowest quantities from both wood and charcoal (Bertschi *et al.,* 2003). The large variation compared to Marufu's work (1999) may be that the techniques used to measure emissions are different.

All biofuel data in Africa have been collected in campaign style, i.e. collected over a short period of time. There have not been any annual measurements, only annual estimates based on these data sets. Seasonal variation in southern Africa, particularly in terms of temperature and rainfall, can be significant and could therefore lead to a large difference in the use of biofuel between summer and winter. It is therefore important for improving annual estimates that biofuel consumption and the emissions produced are measured and calculated for each month of the year, and this is how this project aims to improve the existing biofuel consumption and trace gas emission numbers.

Table 2.7: Annual trace gas emissions from domestic biofuel burning in Zambia, 2000 (Bertschi *et al.,* 2003).

Trace compounds	**Emissions from different biomass sources (Tg C yr^{-1})**	
	Wood	**Charcoal**
CO_2	9.8	3.3
CO	0.61	0.36
CH_4	0.06	0.04
NO_x	0.01	0.00

Chapter 3

Research methodology

3.1 Biofuel emission estimates

To accurately estimate emissions, knowledge of quantities of biofuel consumed, efficiency of the technologies employed to burn the fuel and the emission factors of the corresponding trace gas species of interest are needed (Streets and Waldhoff, 1999; Bhattachayra *et al.,* 2000). An emission factor is defined as the mass of a compound released during the combustion per unit mass of dry fuel (Ludwig *et al.*, 2003).

There are two methods for estimating trace gas emissions. The first one requires biofuel consumption rate and emission factors (Andreae and Merlet, 2001; Ludwig *et al.* 2003; Streets and Waldhoff, 1999; Bhattachayra *et al.,* 2000). Emission rates are estimated by multiplying biofuel consumption by the emission factor, as it was done by Ludwig *et al.,* 2003. The second method is very similar except that the emission factor is based on an emission ratio using the carbon balance method. This requires knowledge of the carbon content of the fuel as well as moisture content and the non carbon ash content. Yevich and Logan (2003) used this method to calculate their emission estimates. Carbon in the preburned biofuels or residue can vary from 35% by weight to 54%, but Marufu *et al.* (1999) assumed it to be about 50%. In this study the former method was used because it only requires information on emission factors, which has already been determined for southern African fuels (table 3.1), and consumption rate, which is relatively easy to measure. Furthermore, this method has previously been used to calculate emission estimates in some southern African countries (Marufu *et al.,* 1999), so using the same method makes the results in this study comparable to previous studies.

Table 3.1: Average emission factors calculated from the combustion of different biofuels in Zimbabwe and West Africa. Emission factor for wood, maize residues and cattle dung are based on on-line measurements conducted in Zimbabwe (Ludwig, *et al.*, 2003), while those for charcoal are from similar measurements conducted in west Africa (Brocard and Lacaux, 1998). Emission factors are given as g C or N per kg of dry fuel. MCF is the moisture correction factor.

Type of fuel	Emission factors				
	MCF	CO_2	CO	NO	CH_4
Zimbabwe					
Fuel wood	0.85	450	43	0.52	1.5
Maize residues	0.95	469	27	1.7	4.49
Cattle dung	0.95	439	36	4.41	4.49
W. Africa					
Charcoal	1	170	25	0.29	0.5

3.2 Consumption rate measurements

The project covers the southern African countries of Mozambique, Malawi, Zambia, Zimbabwe, Namibia, Botswana and South Africa. In each country three households were selected for monitoring. Selection of the households was done in a stratified sampling, with one household on the southern part of the country, one in the central and one in the northern part of the country. The location of the sites is shown in figure 3.1. The sites are all situated along or near major roads due to accessibility to the villages for monitoring and data collections. The deep rural remote villages could not be reached as there are no roads for vehicles to go through to most of the rural areas. It is also a limitation to the study and could bias the results slightly. This is something that could be improved in future studies.

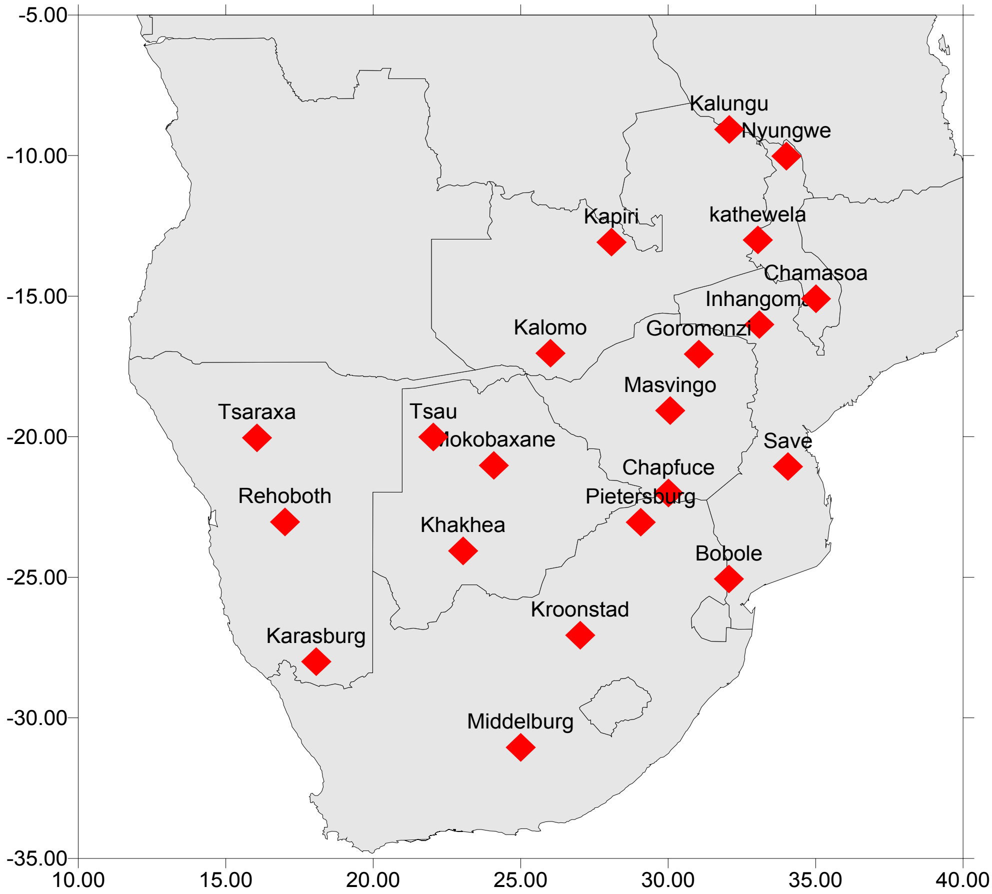


Figure 3.1: A map of southern Africa indicating the location of the sites where biofuel consumption rates were measured.

Each household was equipped with a scale (fig 3.2) and a log book in which they recorded the quantity of biofuel used at each cooking session (breakfast, lunch and dinner) as well as the number of people in the house for each cooking session (example of this record sheet is given in Appendix A). The quantity (kg) of fuel and number of people were recorded on a daily basis. The occupants of the household were interviewed to obtain additional information regarding the use of biofuels (questions asked for interviews are given in Appendix B). The collected data was used to calculate monthly consumption rates (kg person^{-1} month^{-1}) (results discussed in detail in Tshiakalanke, 2005).

Figure 3.2: A picture shows the occupants in Joro, north of Zimbabwe, weighing fuel wood before cooking for the morning session.

3.3 Emission estimate calculations

Emission estimates are calculated for various gases as described by Ludwig *et al* (2003):

Emission estimate (g C per kg) = BC x MCF x EF

Where MCF is the moisture correction factor, which for this study was taken from Brocard and Lacaux, 1998; BC is the biofuel consumption rate (kg of wood per person per month) and EF is the emission factor (g C or N per kg of a fuel burned). EFs used are those given in table 3.1.

Consumption data was collected from May 2003 to February 2004 in all countries. It should be noted that the project is on going so as to obtain annual data, however only 9 months of data were collected for this study because of the time limits of the project. Data for the missing months (summer months) were estimated from the mean summer monthly values so as to be able to obtain an initial annual emission value.

Emission estimates were multiplied by the rural population (United Nation, 2003) of each country so as to determine biofuel emissions per country. The assumption was made that biofuel is used only by the rural population of each country. This assumption was also made by Marufu *et al.* (1999) and Ludwig *et al.* (2003).

Chapter 4

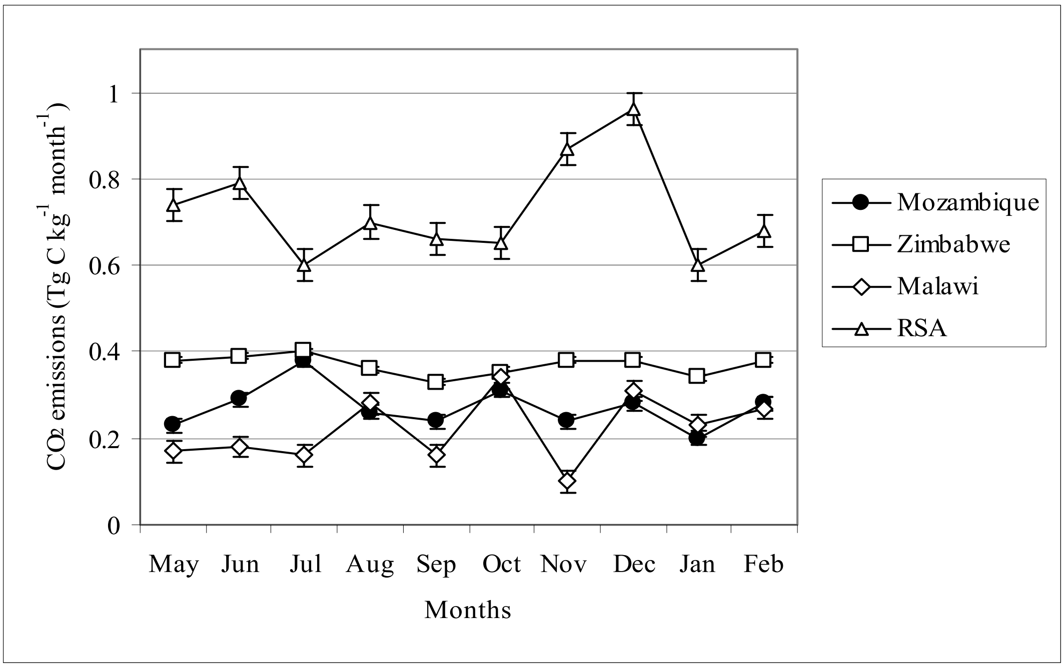
Results

4.1 Monthly variation of trace gas emissions in southern African

Monthly variation of trace gas emissions is influenced by consumption rate and fuel type. For example, burning of maize residues produce higher emissions (particularly for NO and CH_4) than other fuel types and it is mostly burned in the winter season after the harvest period. This leads to higher NO and CH_4 emissions in winter in the countries that use maize residue. On the other hand, consumption rate and population density influence the country emission rates.

RSA shows the highest trace gas emissions from biofuel consumption in southern Africa (figures 4.1 to 4.4), with highest emissions occurring in December. These high December values are due to high biofuel consumption during this month because many household members return home for the holidays and there is an increase in cooking for the festive season. In South Africa there is no clear or significant seasonal variation in emissions. Zimbabwe, the second highest contributor of CO and CO_2, also shows no significant seasonal trend with emissions. Botswana has the lowest emissions in the region, with values for all gases being close to zero. This is attributed to fuel wood scarcity in the country and the low rural population density. No seasonal variation was detected in Botswana, as is the case for Namibia. In Zambia NO and CH_4 emission are elevated during August, December, January and February and is the same trend for CO_2. This is mainly due to the use of different fuel types (which will be highlighted in the next section), but once again emissions are higher in mid summer probably due to the returning workers over the festive season. Emissions are, however, not higher during winter as may have been expected.

Mozambique shows some seasonal variation in emissions, with higher CO_2 and CO emissions in June and July and slight increase in October and December (fig 4.1 and 4.2). Malawi shows highly variable monthly emissions and this is mainly due to the supplementary use of maize residue.



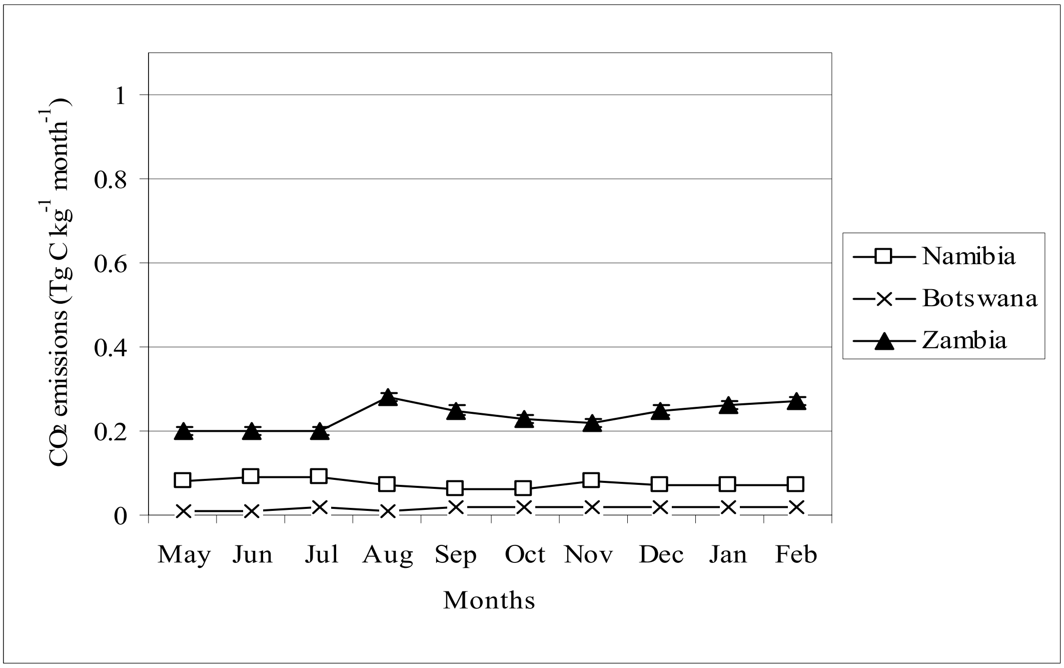
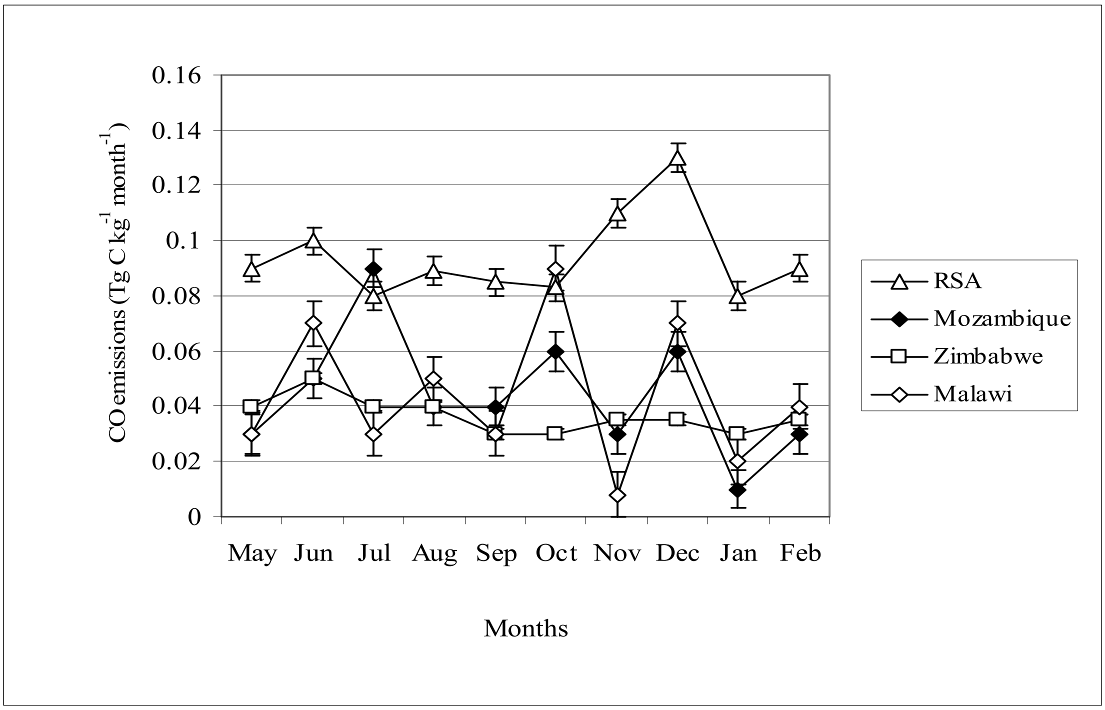


Figure 4.1: CO_2 emission estimates between May 2003 and February 2004 for Mozambique, Zimbabwe, Malawi and RSA (top) and Zambia, Botswana and Namibia (bottom). The bars represent the standard error.



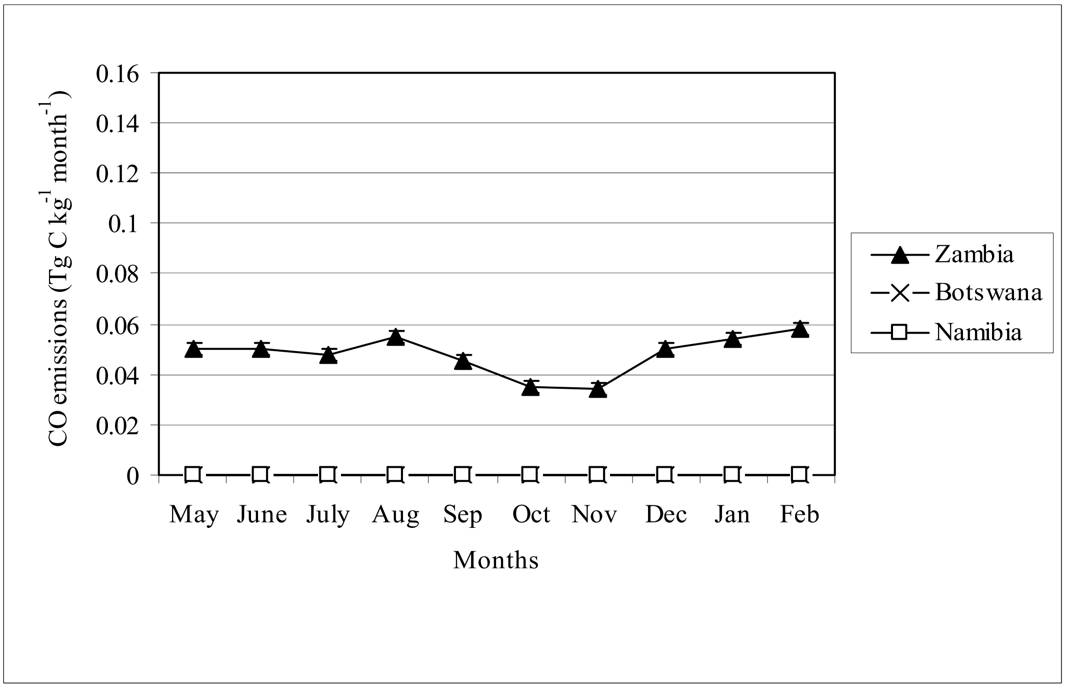
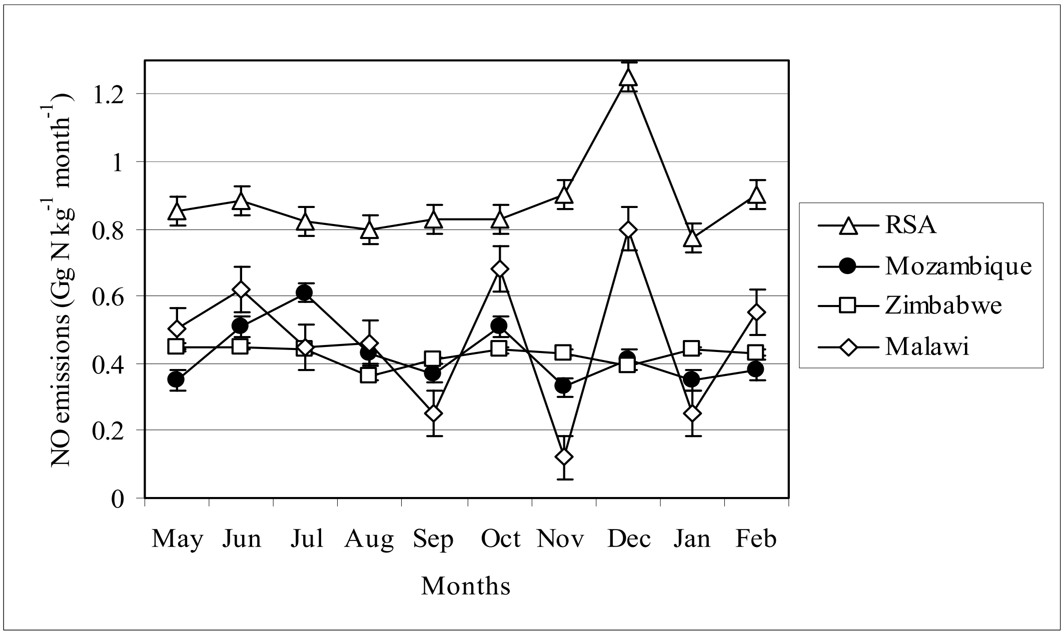


Figure 4.2: CO emission estimates between May 2003 and February 2004 for Mozambique, Zimbabwe, Malawi and RSA (top) and Zambia, Botswana and Namibia (bottom). The bars represent the standard error.



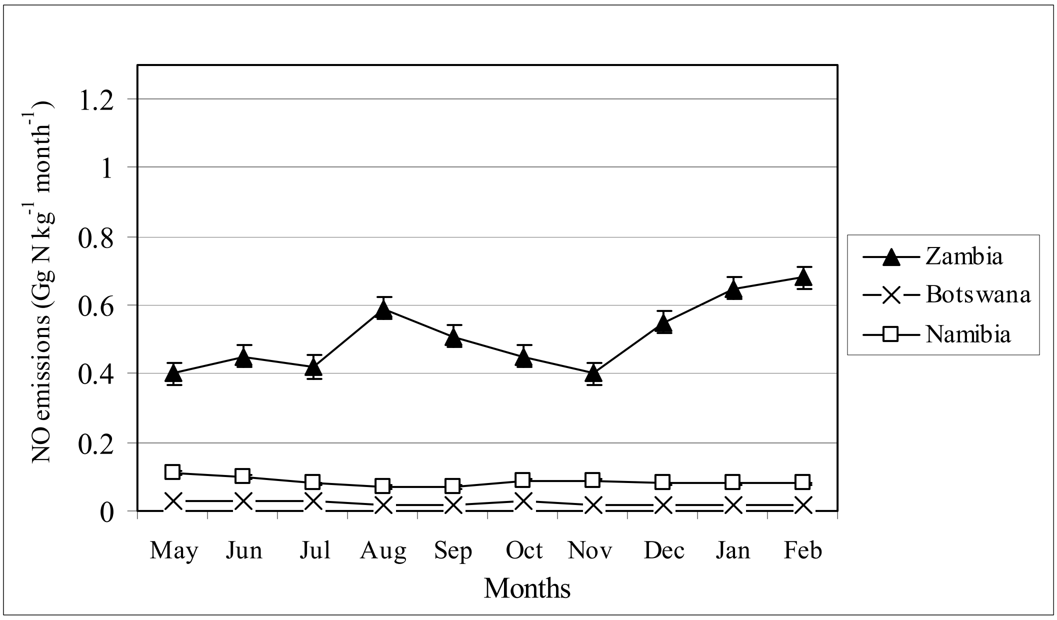
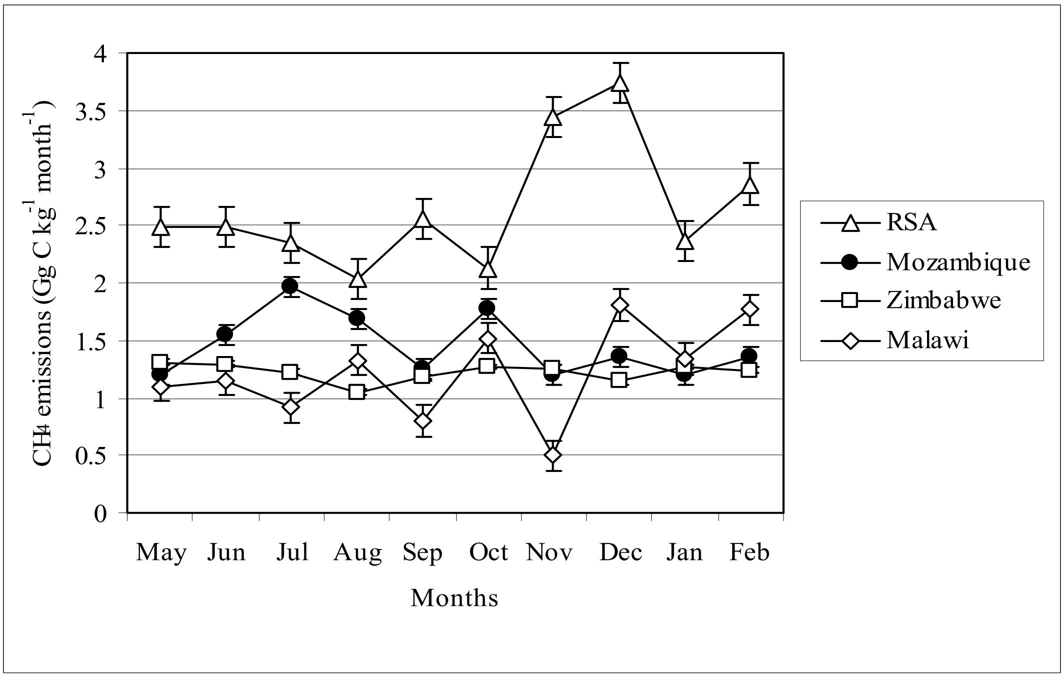


Figure 4.3: NO emission estimates between May 2003 and February 2004 for Mozambique, Zimbabwe, Malawi and RSA (top) and Zambia, Botswana and Namibia (bottom). The bars represent the standard error.



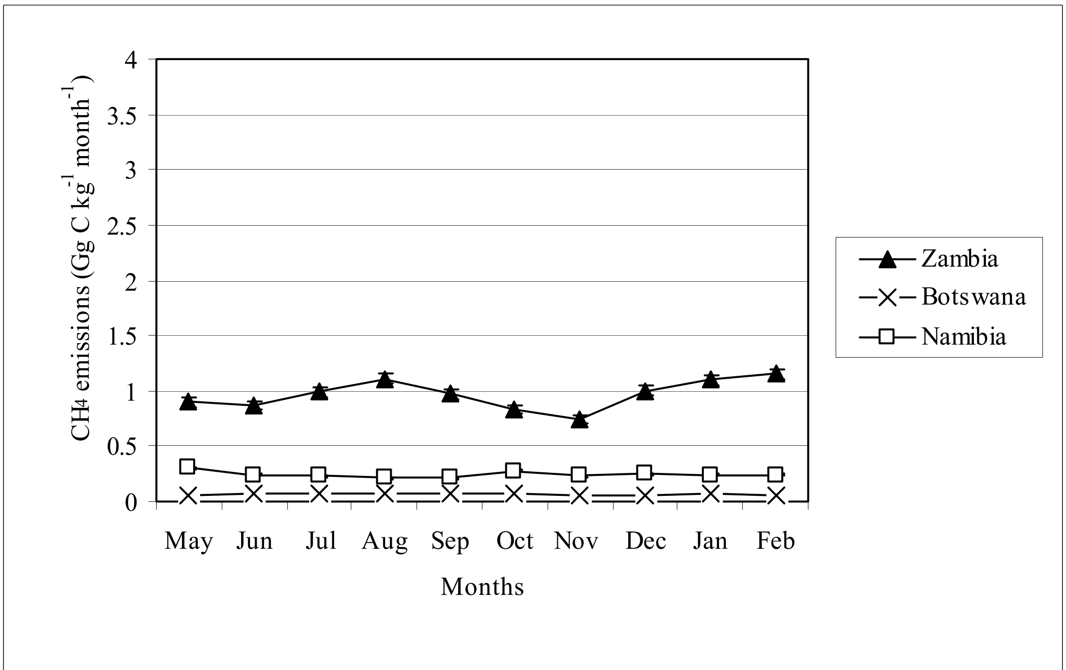


Figure 4.4: CH_4 emission estimates between May 2003 and February 2004 for Mozambique, Zimbabwe, Malawi and RSA (top) and Zambia, Botswana and Namibia (bottom). The bars represent the standard error.

4.2 Effect of variation in fuel type on monthly emissions

The seasonal trend within each country is similar for each trace gas. In Zambia, Mozambique and Malawi there are slight differences due mainly to the use of different fuel types which causes a change in emission ratios. In Malawi wood was used every month, while in some months it was supplemented with the use of maize residue (figure 4.5 and 4.6). Maize residue was found to be used during the months of May to August, October and December to February. May to July is the usual harvest period however maize residue was used in the other months due to the late harvest period in the areas close to Lake Malawi. Figure 4.5 and 4.6 show how changes in fuel type affect the monthly emission ratios. The use of maize residue increased the CH_4 and NO emissions from Malawi, relative to the other countries. There was no clear seasonal variation throughout the year in Malawi.

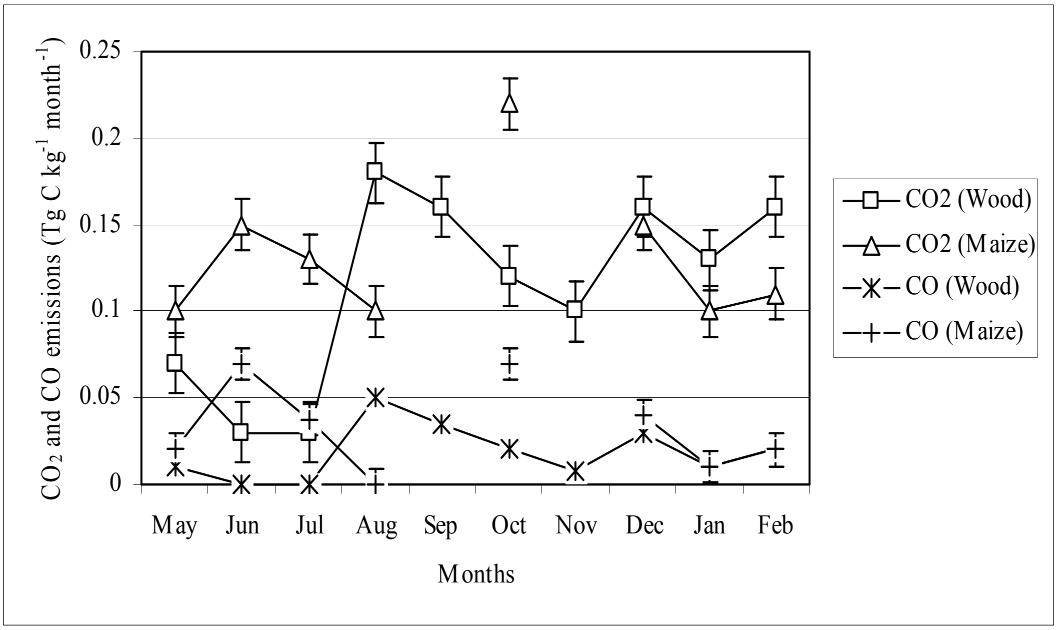


Fig 4.5: Monthly CO_2 and CO emissions in Tg C kg^{-1} $month^{-1}$ from different fuel types in Malawi (May 2003 to February 2004).

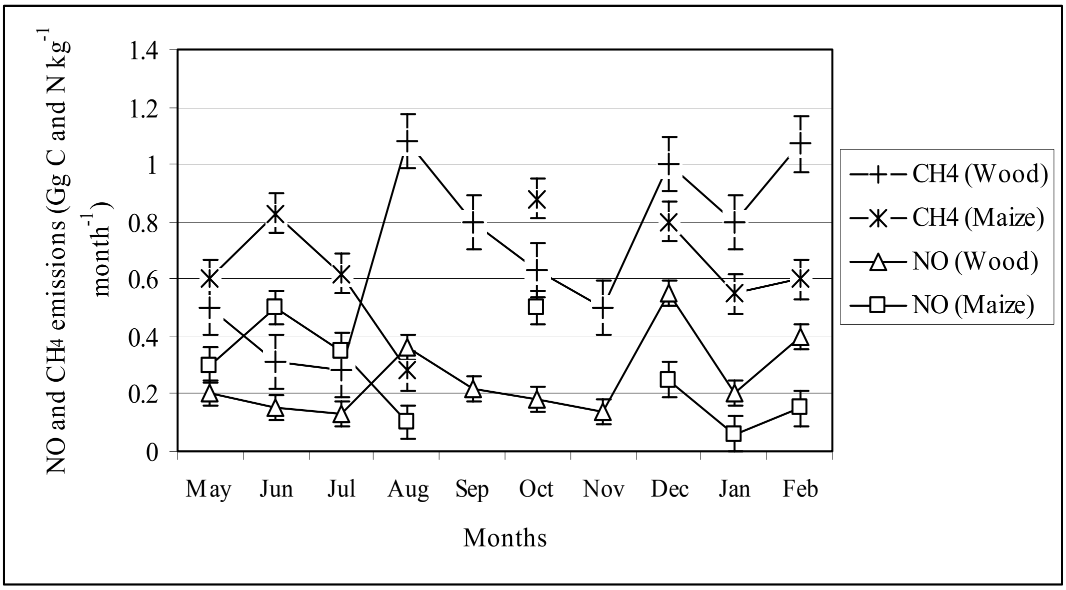


Fig 4.6: Monthly NO and CH_4 emissions in Tg C kg^{-1} month^{-1} from different fuel types in Malawi (May 2003 to February 2004).

In Zambia wood is used every month, and between May and November it is supplemented with charcoal. The increased emissions seen in December to February are not due to the use of more than one fuel type but rather due to an increased consumption of wood (figure 4.7 and 4.8). In Mozambique charcoal was also used as a supplementary fuel between the months of May and August as well as in October. The charcoal use is however relatively small and so it doesn't have a huge impact on the monthly emission variation (figure 4.9 and 4.10).

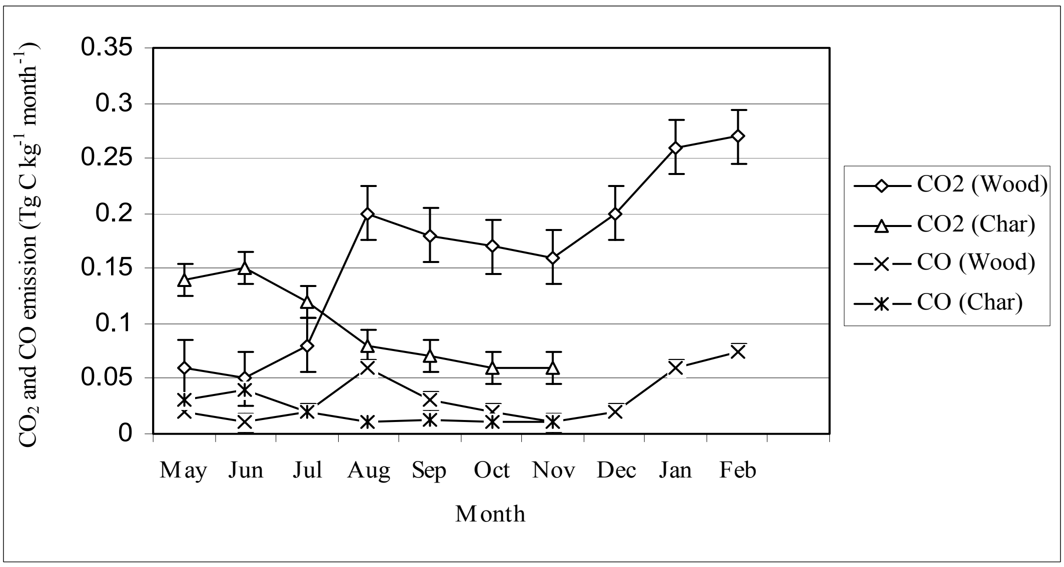


Fig 4.7: Monthly CO_2 and CO emissions in Tg C kg^{-1} month^{-1} from different fuel types in Zambia (May 2003 to February 2004).

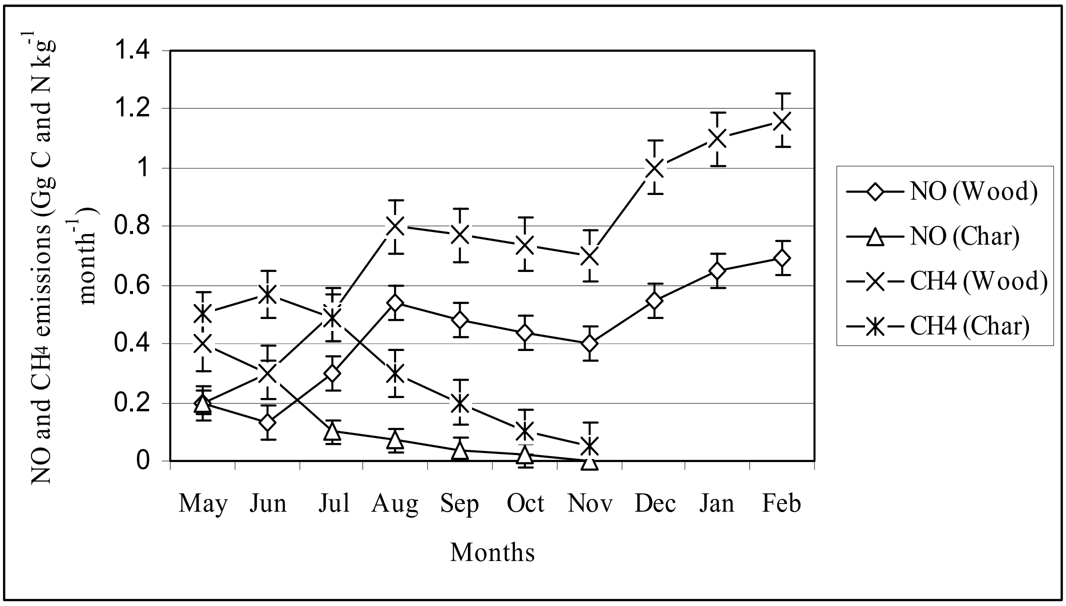


Fig 4.8: Monthly NO and CH_4 emissions in Tg C kg^{-1} $month^{-1}$ from different fuel types in Zambia (May 2003 to February 2004).

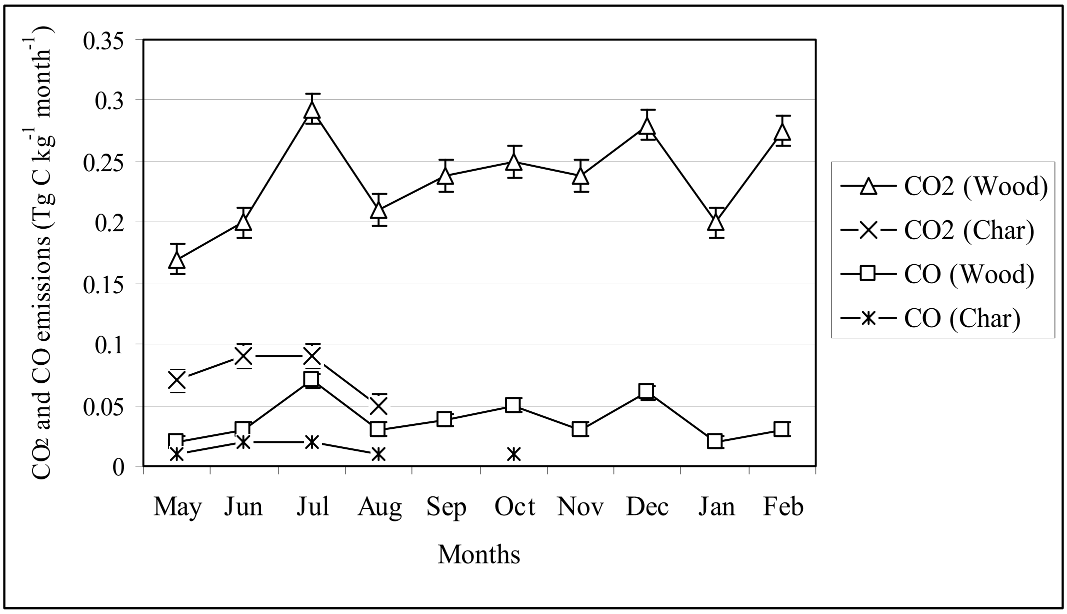


Fig 4.9: Monthly CO_2 and CO emissions in Tg C kg^{-1} $month^{-1}$ from different fuel types in Mozambique (May 2003 to February 2004).

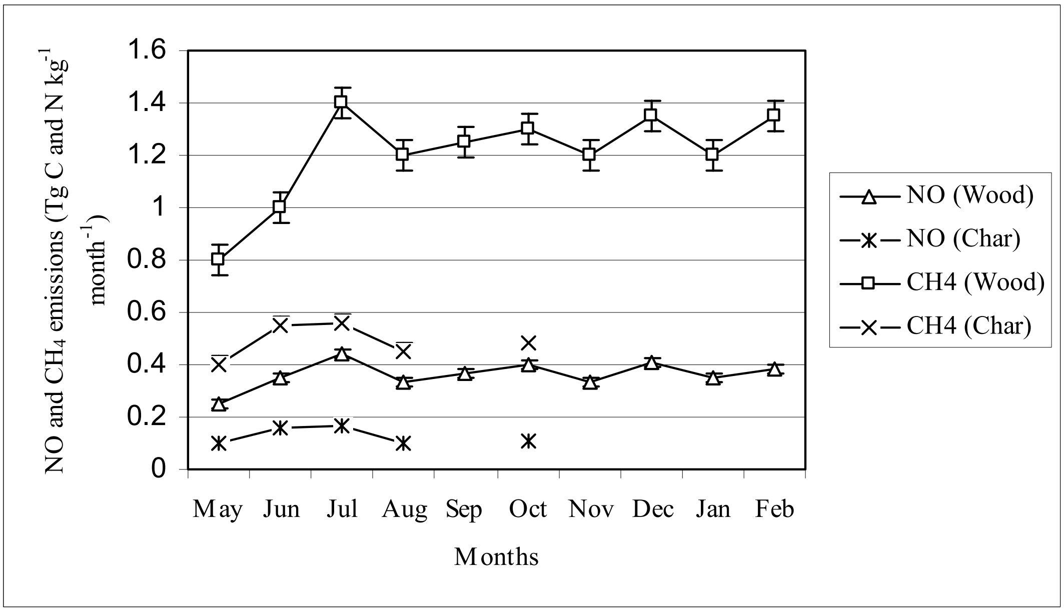


Fig 4.10: Monthly NO and CH_4 emissions in Tg C kg^{-1} month^{-1} from different fuel types in Mozambique (May 2003 to February 2004).

South Africa appears to have very little seasonal variation (figure 4.1 to 4.4) in emissions, however separating emissions out from different fuel types shows a lot of variation from month to month (figure 4.11 and 4.12). Emissions are high in December and January mainly due to increased consumption of wood. CO_2 emissions from fuel wood decline from June to August while CO_2 emissions from charcoal increased during this time (fig 4.11). CH_4 emissions were much higher from fuel wood than from charcoal (fig 4.12). There were no clear seasonal patterns in the use and emissions from fuel in South Africa.

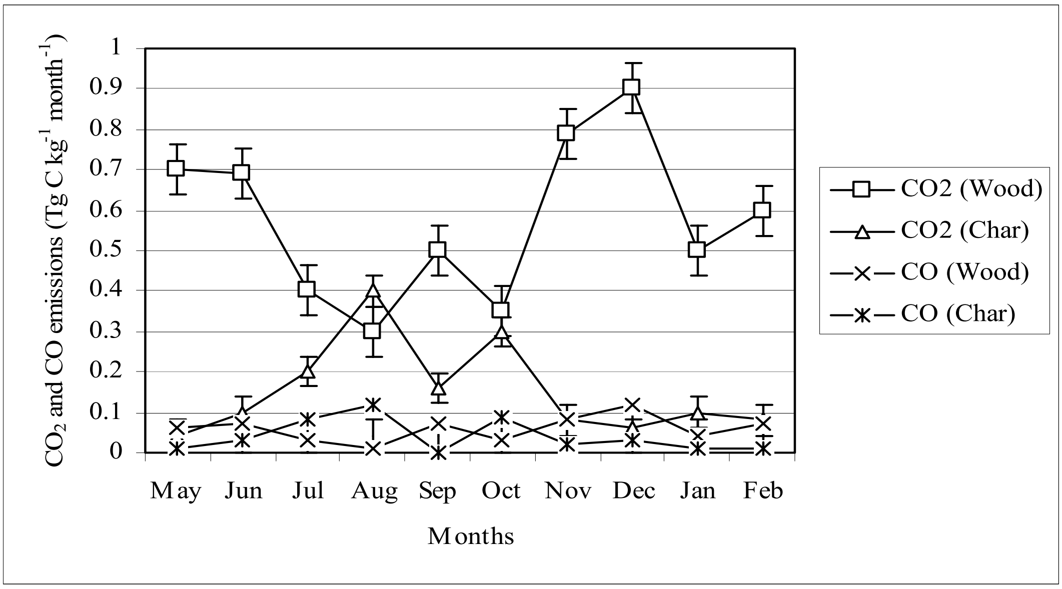


Fig 4.11: Monthly CO_2 and CO emissions in Tg C kg^{-1} month^{-1} from different fuel types in RSA (May 2003 to February 2004).

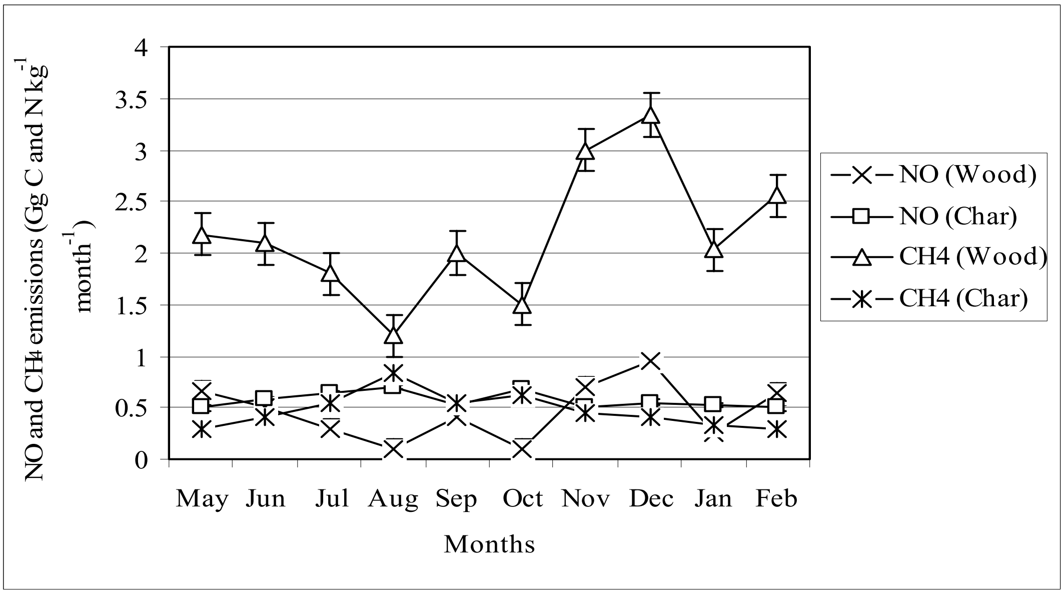


Fig 4.12: Monthly NO and CH_4 emissions in Tg C kg^{-1} month^{-1} from different fuel types in RSA (May 2003 to February 2004)

4.3 Contribution of the various fuel types to emissions across southern Africa

Fuel wood is the dominant fuel type used in all southern African countries and therefore contributes significant amounts (82 – 90%) of trace gases to the budget of each country. Charcoal is used in RSA, Mozambique and Zambia and contributes 6% to 8% to the biofuel trace gas budget of southern Africa (fig 4.13 to 4.16). Malawi is the only country that uses maize residues and the burning of maize residue contributes between 2% and 10% to the CO_2, CO, NO and CH_4 southern African biofuel trace gas budget (fig 4.13 to 4.16). Charcoal produced higher CO_2 and CO emissions (fig 4.13 and 4.16), whereas maize residues contribute greater amounts of NO and CH_4 (fig 4.9 and 4.10).

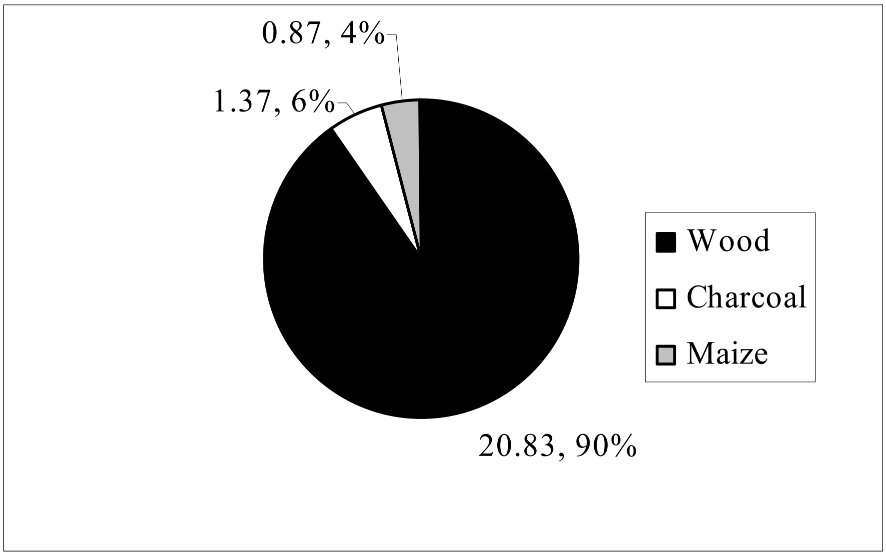


Fig 4.13: The contribution of various fuel types to the annual CO_2 emission budget for southern Africa. The values given are the annual emission rate (in Tg C yr^{-1}) and the percentage contribution to the total.

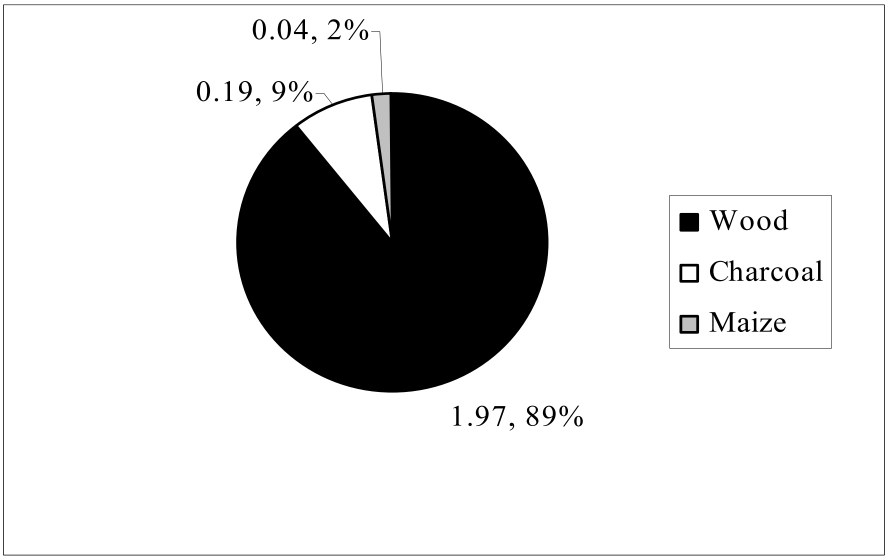


Fig 4.14: The contribution of various fuel types to the annual CO emission budget for southern Africa. The values given are the annual emission rate (in Tg C yr^{-1}) and the percentage contribution to the total.

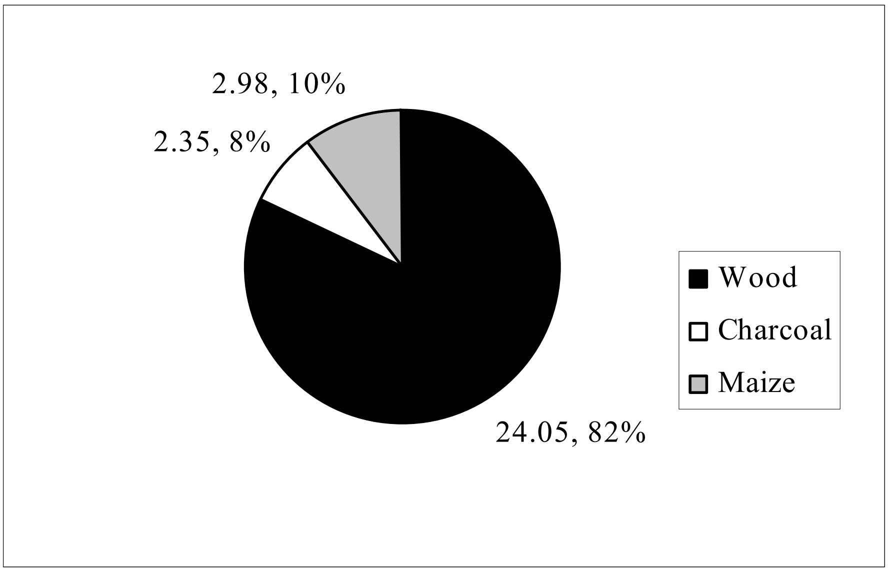


Fig 4.15: The contribution of various fuel types to the annual NO emission budget for southern Africa. The values given are the annual emission rate (in Tg N yr^{-1}) and the percentage contribution to the total.

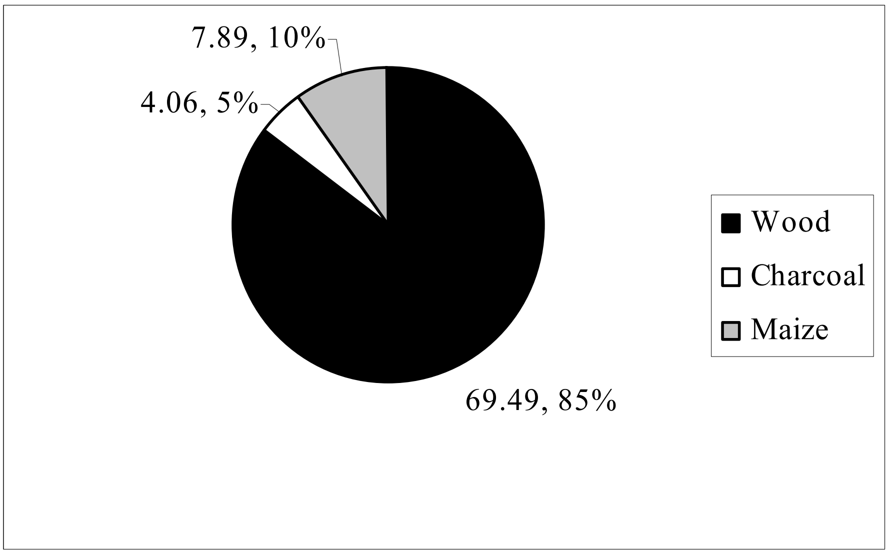


Fig 4.16: The contribution of various fuel types to the annual CH_4 emission budget for southern Africa. The values given are the annual emission rate (in Tg C yr^{-1}) and the percentage contribution to the total.

4.3 Annual emission estimates

Annually southern African countries are estimated to produce a total of 23.03 Tg C as CO_2, 2.22 Tg C as CO, 29.42 Gg N as NO and 81.43 Gg C as CH_4 from domestic biofuel burning (table 4.1). RSA is the biggest contributor to all trace gases, and this is mainly a function of the large rural population in South Africa. Zimbabwe is the second highest contributor even though it has a smaller rural population than Malawi and Mozambique. This is because Zimbabwe has the highest fuel wood consumption (Tshikalanke R.P, MSc Report) of these three countries. Botswana contributes the lowest emissions to the region because of its small rural population and low consumption rates. Mozambique contributed higher CO_2 and CO than Malawi due to higher biofuel consumption, while Malawi contributed higher NO and CH_4 than Mozambique due to the use of maize residues as a biofuel.

Table 4.1: Annual emission estimates of CO_2, CO, NO and CH_4 from domestic biomass burning in southern Africa.

Country	**Rural population in 2003 (x1000)**	**Emission estimate**			
		CO_2 (Tg C yr^{-1})	**CO (Tg C yr^{-1})**	**NO (Gg N yr^{-1})**	**CH_4 (Gg C yr^{-1})**
RSA	19 389	9.12	0.89	10.77	30.25
Mozambique	12 140	3.15	0.32	3.86	10.36
Malawi	10 133	2.64	0.22	5.09	13.97
Zimbabwe	8 390	4.42	0.42	5.10	14.73
Zambia	6 951	2.57	0.27	3.29	8.35
Namibia	1 344	0.88	0.08	1.02	2.94
Botswana	865	0.25	0.02	0.29	0.83
Total	*59 212*	*23.03*	*2.22*	*29.42*	*81.43*

Chapter 5

Discussion

5.1 Biofuel combustion practice

Biofuel combustion data was collected from indoor huts (kitchen) separated from the main house. The fire was made on a circular, gentle depression on the floor. In most cases the fire is situated behind the door, or on the side behind the door to minimize draught. A three-legged metal frame is usually placed above the fire place to hold the pot above the fire (fig 5.1 and 5.2). Exhaust gases are released into the hut, which is ventilated through the doorway, the window, and a small gap between the wall and the thatched roof.

The duration of the combustion session depends on what was cooked. In winter often more fuel was added after cooking for heating the hut and thus prolonging the burning period. Burning practices and durations vary from country to country. Climate, and thus seasonal change, and cooking requirements are the main determinants of fire duration and intensity. Small pieces of wood are added in a fire place below the pot so as to increase the intensity of fire and cooking performance. This type of combustion practice, which occurs all over the region, has high flaming temperatures and favours the formation of products of complete biofuel combustion in which mainly CO_2, CO and NO are produced (Kituyi *et al.,* 2001). This combustion practice was applied over all the countries that the research covered, and it resulted in high emissions throughout the sub-continent.

Depending on the fuel availability in the different areas, households either let the fire wood burn down on its own or quench it with water soon after it was used. This has implications for trace gas emissions in that the longer the duration of the fire the more trace gases are produced. Countries that have plenty of biofuel such as Zimbabwe, RSA and Zambia usually burn fires for longer and emit more trace gases than other countries which have limited biofuel resources.

Fig 5.1: A cooking area in Karasburg, south Namibia, showing the small pieces of wood that is ready to be added on a fire. A semi–circle frame was placed around the fire so as to reduce wind.

Fig 5.2: A fire place in an informal kitchen in Taraxa, central Namibia. A three-legged metal frame is erected above the fire and a pot placed above the fire for cooking.

5.2 Emissions from different fuel types

Three biofuel types were found to be used among all southern African countries, notably fuel wood, charcoal and maize residues.

5.2.1 Fuel wood

The consumption rate of wood was higher than the other fuel types in southern Africa mainly due to its abundance and availability (figure 5.3), as well as its low cost. Wood is also preferred as a fuel since it does not produce as much smoke as charcoal and maize residue. Streets and Waldhoff (1999) showed that areas that burn large quantities of fuel wood have a higher proportion of CO_2 and CO, and this is evident in this study with wood contributing 90% and 89% to the regional CO_2 and CO budget respectively. Wood has higher trace gas emissions specifically for CO_2 and CO, while maize residues produce higher emissions of CH_4 and NO.

Figure 5.3: Mozambique has relatively dense vegetation, thus fuel wood is readily available.

Wood was used in all countries but in Botswana, Namibia and Zimbabwe it was found to be the sole source of domestic energy generation. Previous studies indicate that cow dung has been used as an alternative energy source in Botswana and Zimbabwe (Marufu *et al.,* 1997), but only in very small quantities (<3% of household energy needs) and only in areas that are fuel stressed. None of the residents in this study used cow dung as a fuel source as it produces large amounts of smoke, which is irritating to the eyes, and it also produces a very unpleasant smell.

Fuel wood in rural areas is free of charge from the surrounding environment, thus areas with high fuel wood availability tend to have higher consumption rates. Large quantities of trace gases are emitted in areas where there is enough fuel wood for domestic energy generation. For example, Mozambique has abundant, woody and dense vegetation across the entire country, particularly along the coastal areas, and rural villagers do not have to travel long distances to obtain wood (fig 5.3). On the other hand, interviews conducted in Botswana showed that fuel wood combustion is very low because rural villagers travel long distance from the village to the source (approximately 2 to 6 km). Distance from the village to the source has a tendency of reducing the level of consumption and thus emissions particularly in Botswana. This is seen in other countries, such as Chad, which have low fuel availability (Yevich and Logan, 2003). Residents in these regions use fuel in a more efficient way, once cooking is finished fire is quenched with water so as to avoid unnecessary fuel wastage.

5.2.2 Charcoal

Charcoal is processed from fuel wood and this process, called carbonization, also produces trace gases. The carbonization process is generally inefficient, and it is estimated that it can emit 60% by weight of the original wood as CO_2, CO and CH_4 (Kituyi *et al.,* 2001). Estimates suggest that six to twelve tons of wood are required to make one ton of charcoal (Yevich and Logan, 2003). These emissions have not been included in the total emission estimates calculated in this study, only emissions during the use of charcoal in households has been calculated.

Charcoal is produced and either sold within the country or exported to neighboring countries. Unlike wood, charcoal costs money. The price of charcoal varies with country and place. In areas that are closer to the town charcoal is more expensive than areas that are far from the town since charcoal is made in rural area where there is a high dense of vegetation. For example, in Mozambique a 50 kg bag of charcoal is 90 000 Mozambique Meticals (MT) (or R30) if it is bought close to town, however as one moves further away from the town it costs MT 75 000 (or R25). In Zambia charcoal price is similar however the price is the same irrespective of the proximity to town. Many rural residents cannot afford to pay for fuel and would therefore rather use freely available wood, thus charcoal consumption rates in rural areas in all countries are lower than fuel wood consumption rates. The CO_2, CO, NO and CH_4 emission factors for charcoal are much lower than wood or maize residue thus biofuel emissions would be reduced if more charcoal and less wood was used in the future.

In addition to wood, only three countries were found to use charcoal, namely RSA, Zambia and Mozambique. In RSA charcoal was used throughout the year with 10% of household biofuel being charcoal and the rest fuel wood. Charcoal was used mainly during the evening for cooking and space heating, while fuel wood was used during the day. This is because charcoal produces less smoke than wood, therefore is more suitable for space heating in the evening. In Zambia charcoal was only used from February to August (winter months), and was used mainly in the evening for space heating. Charcoal contributes 40% of biofuel use in Zambia. In Mozambique charcoal was used throughout the year with large quantities of charcoal burning occurring during winter for space heating and it contributes 25% to the biofuel use in Mozambique. Zambia and Mozambique are large producers of charcoal and hence the increased used of charcoal in these countries (Anyamba *et al.*, 2002). The rural population of RSA uses charcoal as well, and much of the charcoal is produced within the RSA, but some is imported from other countries such as Namibia. The charcoal is packaged and sold mainly in towns or at petrol stations along main roads. In some rural regions coal is used instead and this is mined in local mines around the country including Mpumalanga, Gauteng and North West. The low consumption rates of charcoal in southern Africa and low emission factors led to charcoal contributing only 6%, 9%, 8% and 5% to the total CO_2, CO, NO and CH_4 budget over the entire region (fig 4.13 to 4.16). This proved to be the similar trend with charcoal and fuel wood consumption in Zambia, charcoal produced lesser emissions compared to fuel wood, wood contributed 9.8 Tg C yr^{-1} CO_2 whereas charcoal contributed 3.3 Tg C yr^{-1} CO_2, 0.61 Tg C yr^{-1} CO from fuel wood and 0.36 CO from charcoal (Bertschi *et al.,* 2003).

5.2.3 Maize residues

Maize residue is a seasonal, substitute fuel which is used during winter to spring season as a result of harvest period. Maize residue does not burn as easily as the other fuel types and it produces a lot of smoke in the hut, thus it is only used for domestic energy production if and when other fuel types are not available and if there is an abundance of maize. The NO and CH_4 emission factor for maize residue is higher than that for wood and charcoal. Due to its high emission factors, country emissions would be much higher if maize residue was used throughout the year.

In this study maize residue was only found to be used in Malawi. Malawi has three seasons, namely dry (August – October), cool (May – July) and wet (Nov – April) (Hahmann and Dickinson, 2000) and rainfall is between 635 and 3050 mm depending on altitude and position of the area (Hahmann and Dickinson, 2000). Although rainfall varies, most parts if not all, receive sufficient rainfall to grow crops, particularly maize. Other countries do receive enough rainfall for maize cultivation; however, preference for domestic energy is given to other fuel types including fuel wood and charcoal. In contrast to this study Marufu *et al.* (1996 and 1997) found that maize residue was also used in Zimbabwe and Namibia and that it contributed approximately 5% to each countries biofuel trace gas budget. Maize residue use was found to be seasonal in this study, with an increased use around autumn and winter which is the harvest period. CH_4 and NO emissions increased during this time because of the high CH_4 and NO emission factors for maize residue (Marufu *et al.,* 1996).

Yevich and Logan (2003) suggested that the use of maize residue may increase as one moves into eastern Africa as about 75% of maize is grown in Eastern part of Africa including Kenya, Malawi and Tanzania. In these regions there is heavy rainfall and a long growing season, which enable villagers to use more maize residues for domestic energy generation. This trend of increased use of maize residue in the eastern parts of Africa was found to be true for this studying in Malawi precisely, except that no other countries even used maize residue. There could be several reasons for this. Firstly, it may have been a bad year in terms of rainfall and cultivation and thus the small use of maize residue previously found in other southern African countries was reduced to zero. It was reported by the household occupants in Zimbabwe that maize residues were not used in 2003 and 2004 due to reduced cultivation as a result of low rainfall. Secondly, it could be that other fuel types were more accessible than maize residue in other countries; and thirdly, it may be that maize residue is only used in certain regions of each country and that the sampling sites in this study (3 sites in each country) did not include these areas. The households in this study are in neighbouring villages to those where Marufu *et al.* (1996) found maize residue to be used (Chihota, Honde, Svosve and Dombotombo), however Marufu *et al.* (1999) also showed that only one out of 9 villages used maize residue. It is therefore possible that the sites selected did miss the few households that use maize, but it is indicated to be a very small percentage of the population and will therefore not make a significant difference to country emissions.

Emissions are likely to change for the northern parts of Africa since agricultural residues from millet, sorghum, wheat and barley are preferred over maize as a source of domestic energy generation (Yevich and Logan, 2003). The combustion of these products will have different emissions from the maize and is something that needs to be investigated in future studies.

5.3 Monthly and seasonal variation in emissions from biofuel combustion

One of the hypotheses of this study was that emissions from domestic burning would increase in the winter periods due to increased consumption rates. Generally this does not appear to be the case. There is month to month variation, particularly in RSA, Mozambique, Zambia and Malawi, but seasonal variation is not obvious. In countries that use more than one fuel type, even if the consumption rates show seasonal variation it does not mean that emissions will show the same pattern. This is because the various fuels have different trace gas emission factors and so as soon as a new fuel type is introduced the trace gas emission ratios change. The countries that show the highest monthly variation are the ones that use more than one fuel type.

Below each country is discussed separately as each one has different climatic and social conditions which cause monthly variation in consumption and emissions.

5.3.1 RSA

Many rural South African villages are electrified, but electricity is expensive so it is only used for lights, radio or TV and fuel wood is still used for cooking and space heating. Therefore one would still expect a seasonal variation in consumption and emissions, but this was not found to be the case. Emissions increased during December in many areas of RSA. Household numbers increased during the festive season as many residents return to the rural homes during the holidays and this leads to high consumption rates and thus emissions during this period. There were very low CO_2 emissions in July due to low fuel wood consumption at one site (Tshikalanke R.P, 2005) and an increased use of charcoal. This pattern was similar for CO. Emissions of NO and CH_4 were low in June and July due to higher charcoal use and lower fuel wood combustion. There is a clear pattern that charcoal emissions increased in June, July and August for all gases and the opposite is true for fuel wood as wood consumption during these months is decreased. This pattern of increased charcoal use in winter may be because charcoal is preferred for space heating and winter is the time when the need for space heating increases.

5.3.2 Zambia

In Zambia emissions were not found to be influenced by seasonal changes (fig 4.1 to 4.8). Much of Zambia is covered by woodlands which contain hardwood (Anyamba *et al.*, 2002) and there is a plentiful supply of wood. This is one of the reasons for the high production of charcoal in this country. Zambia has a cool and dry season (May to August), a hot and dry period (September to November) and a warm and wet season (December to April). In the warm, wet season wood is the dominant fuel used in rural households, whereas charcoal is used more often in the hot and dry season. In Zambia emissions are generally higher between December to February due to high fuel wood usage (fig 4.1 and 4.2), while the use of charcoal together with a lower wood use from September through to November tends to lower the emission rates during these months.

5.3.3 Mozambique

Mozambique has distinct wet and dry seasons, with the dry season extending between May and September and the wet season from December to February (SAAAS, 1970). Rainfall is particularly heavy in the wet season and it reaches 1350 mm annually (SAAAS, 1970). The high rainfall can sustain the woody vegetation in the region which provides plenty of wood for fuel and for the production of charcoal. Fuel wood is used throughout the year with large quantities of both fuel wood and charcoal being used during the dry season for space heating and cooking. Increased consumption in the dry period (June, July and August) does lead to increased emissions to some extent, but it is due to the increased use of charcoal (which has lower emission factors) that the emissions do not show a significant seasonal pattern.

Several southern African countries have dense vegetation which can support high wood consumption, however, due to other aspects consumption of domestic biofuel remains low. Poverty is one of the factors that determine and influence emissions and this is seen in Mozambique. Much of rural Mozambique is extremely poor, such as the Save village in the central part of Mozambique. Fire is mainly set for boiling water, cooking and space heating three times a day, however, in the Save village fire is not used in the morning due to the lack of food. Not setting fire in the morning has reduced the quantity of biofuel combustion and thus the trace gas emissions.

5.3.4 Malawi

As with the other countries there is no detectable seasonal pattern in Malawi. Maize is cultivated during the wet season and harvested on the dry season between May and August. The use of maize residue, however, extends well beyond this harvesting period and it appears to be used every second month throughout the year (i.e. May, June, August, October, December and February). It is unclear, at this stage, why this is the case. During the months that maize is used the CO and CO_2 emissions are slightly lower due to low emission factors for the gases from maize residue (fig 4.5); however, emissions of NO and CH_4 are higher (fig 4.6) due to high emission factors (as indicated in section 5.2.3). Emissions therefore are highly variable on a month to month basis due to the additional use of different fuel types each month.

5.3.5 Zimbabwe, Namibia and Botswana

As in RSA some rural villages in Zimbabwe are electrified but they still use fuel wood for cooking, boiling water and space heating. The tropical climate of Zimbabwe is moderated by altitude and has a rainy season between November and March and a dry period from May to August (Anyamba *et al.,* 2002). Use of fuel wood as an only fuel type and less seasonal change throughout the year, particularly in highland, has led to low variation of emissions in Zimbabwe throughout the year.

In Botswana and Namibia emissions were constant throughout the year. Botswana has a fairly small population and a semi – arid climate, where rainfall is low and seasonal (November to March) and temperatures are high (Dyer, 1982). It has a dry season and wet season in which there is insufficient rainfall for cultivation (Dyer, 1982). Due to the limited cultivation maize residue is not used for domestic energy generation. Vegetation is sparse, mainly because of the low rainfall, but wood is still the only source of fuel used in households in Botswana. Charcoal making does not occur in Botswana because of the limited wood supply. Therefore only wood is used as a biofuel which leads to a reduction in the monthly variation in emissions. It is also very hot throughout the year thus biofuel consumption rates are low and emissions from biofuel burning are constant throughout the year.

Namibia follows a similar trend to Botswana. Beside fuel wood scarcity, emissions in Namibia were also influenced by the use of electricity. In Namibia, as with RSA and Zimbabwe, several households have electricity. In Taraxa and Karasburg, northern and southern part of Namibia, both urban and rural villages are electrified, however, the rural villagers prefer fuel wood for cooking, boiling water and space heating mostly during cold winter and electricity is used for lights, TV and radio. The use of fuel wood in most cases is an electricity cost saving measure. Biofuel trace gas emissions in Namibia are low due to low consumption rates (Tshikalanke R.P, 2005).

5.4 Annual emissions across southern Africa

Factors that determine the total amount of trace gases emitted from biofuel burning in each country are the rural population numbers and the consumption rates. Consumption rate is dependent on fuel availability and this is not only a function of vegetation potential and amount of precipitation received over a year, but it is basically a function of ecosystem carrying capacity (Marufu *et al.,* 1997). Carrying capacity is determined by vegetation density and population density. RSA, Mozambique and Zimbabwe, for example, are extensive with medium to low carrying capacity (SAAAS, 1970), hence high emissions are expected from these countries. Results in this study corroborated this and RSA has the highest emissions of all trace gases with Zimbabwe being the second highest producer. Mozambique has the third highest CO_2 and CO emissions, however, Malawi emitted the highest NO and CH_4 due to the use of maize residue. Marufu *et al.* (1997) also found RSA, Zimbabwe and Mozambique to have the highest emissions in southern Africa. RSA with a rural population of 19 389 000 has the highest trace gas emissions, whereas Botswana with the smallest rural population of 865 000 shows the lowest emissions (table 4.1). Malawi and Mozambique have higher rural populations than Zimbabwe but Zimbabwe contributed higher emissions than these countries due to higher consumption rates.

The annual trace gas emission estimates in this study are less than those estimates given by Marufu *et al.* (1999) (table 5.1 and 5.2). CO_2 and CO estimates are slightly lower (less than 8% lower), however the NO and CH_4 estimates are significantly (30 – 42%) less. There are several reasons for these differences, namely population number, consumption rates, and variation in fuel types used.

Firstly in terms of population numbers Marufu *et al.* (1999) estimated emissions for both rural and urban areas, while this study investigated only rural emissions. This study therefore used a rural population number, totaling 59 212 000 for southern Africa, whereas Marufu *et al.* (1999) used the total population number of 92 347 000. To make the numbers more comparable it would be useful to recalculate Marufu *et al.*'s (1999) annual emission estimates using their consumption rates and the rural population numbers in this study. Due to insufficient information in terms of fuel type break down and consumption values it could not be calculated in this way, thus values were recalculated by scaling the emission numbers relative to the population number differences, i.e. the rural population number for RSA in this study is 46.76% less than the population number used by Marufu *et al.* (1999) thus all emission estimates for RSA were reduced by 46.76% (table 5.3). Comparing the recalculated values (table 5.3) to those of this study (table 5.1) results now show that the CO_2 and CO emissions in this study are higher (25%), NO emissions equal and CH_4 emissions are lower (18%) than the estimates of Marufu *et al.* (1999).

Table 5.1: Annual trace gas emission estimates for rural domestic biofuel burning in southern Africa calculated for 2003/4 from data collected in this study.

Country	Rural population In 2003 (x 1000)	Emission estimate			
		CO_2 (Tg C yr^{-1})	CO (Tg C yr^{-1})	NO (Gg N yr^{-1})	CH_4 (Gg C yr^{-1})
RSA	19 389	9.12	0.89	10.77	30.25
Mozambique	12 140	3.15	0.32	3.86	10.36
Malawi	10 133	2.64	0.22	5.09	13.97
Zimbabwe	8 390	4.42	0.42	5.10	14.73
Zambia	6 951	2.57	0.27	3.29	8.35
Namibia	1 344	0.88	0.08	1.02	2.94
Botswana	865	0.25	0.02	0.29	0.83
Total	*59 212*	*23.03*	*2.22*	*29.42*	*81.43*

Table 5.2: Annual trace gas emission estimates from domestic biofuel burning in southern Africa in 1989 (Marufu *et al.,* 1999).

Countries	Total population in 1994 (x 1000)	Emission estimate			
		CO_2 ($Tg\ C\ yr^{-1}$)	CO ($Tg\ C\ yr^{-1}$)	NO ($Gg\ N\ yr^{-1}$)	CH_4 ($Gg\ C\ yr^{-1}$)
RSA	41 465	8.47	0.76	16.33	37.01
Mozambique	16 004	5.21	0.47	9.70	26.13
Malawi	11 129	2.78	0.28	4.37	17.84
Zimbabwe	11 261	4.06	0.38	6.34	15.68
Zambia	9 456	3.77	0.42	4.55	39.16
Namibia	1 540	0.56	0.05	0.89	2.20
Botswana	1 487	0.22	0.02	0.58	1.11
Total	*92 347*	*25.01*	*2.38*	*42.76*	*139.13*

Table 5.3: Recalculation of Marufu *et al.* (1999) annual emission estimates for rural domestic biofuel burning in southern Africa by scaling the values to the rural population numbers in this study.

Country	Rural population in 2003 (x 1000)	Emission estimate			
		CO_2 ($Tg\ C\ yr^{-1}$)	CO ($Tg\ C\ yr^{-1}$)	NO ($Gg\ N\ yr^{-1}$)	CH_4 ($Gg\ C\ yr^{-1}$)
RSA	19 389	4.51	0.4	8.7	19.71
Mozambique	12 140	4.0	0.36	7.46	20.1
Malawi	10 133	2.55	0.25	4	16.36
Zimbabwe	8 390	3.02	0.28	4.73	11.70
Zambia	6 951	2.77	0.30	3.34	28.79
Namibia	1 344	0.49	0.04	0.78	1.92
Botswana	865	0.12	0.01	0.33	0.64
Total	*59 212*	*17.45*	*1.64*	*29.26*	*99.22*

Secondly, in terms of consumption rates Marufu *et al.* (1999) used consumption rates measured in Zimbabwe only and applied the values to all countries in the region. It was assumed that the dependencies observed in Zimbabwe apply to neighbouring countries. This study improves on Marufu *et al.'s* (1999) in that it incorporates consumption data collected in each country and data that was collected every day during the study period, thus fewer assumptions were made in this study.

The ratio of CO_2/CO is the same in both studies, and the NO/CH_4 ratios are similar. On the other hand the ratios of CO/CH_4 are higher in this study than in Marufu et al. (1999). The difference in emission ratios is due to the change in fuel type. The CO/CH_4 ratio is lower when there is an increased use of maize residue because of the higher CH_4 emission factor for maize. Marufu *et al.* (1999) reported the use of maize residue in Zimbabwe which was then also applied to the other countries. In this study the use of maize residue was only reported for Malawi, and therefore the regional use of maize residue is much lower than that estimated in Marufu *et al.* (1999). This therefore leads to a lower CO/CH_4 ratio in this study as expected.

Emissions were measured from domestic fires in Zambia in 2000 (Bertschi *et al.,* 2003). Measurements were done in Zambia in Kaoma, which is a small city located about 400 km west of Lusaka in the western province of Zambia, and Milumbwa (50 km west of Kaoma). All fires were conducted inside traditional huts. This data lead to annual estimates for Zambia of 13.1 Tg yr^{-1} of CO_2, 0.97 Tg yr^{-1} of CO and 0.1 Tg $yr^{-1}$of CH_4 in the year 2000. This is relatively high compared to the emissions that were estimated in this and Marufu's study, but this may be due to the difference in techniques including their scaling and number of households in a country. In Bertschi *et al.*'s study an open – path Fourier transform infrared spectroscopy was used to quantify emission from domestic fires. Emissions were measured in three open wood cooking fires in three different households around Lusaka and it was measured on a daily basis for a month and then scaled up to country level. Bertchi *et al.'s* (2000) study actually measured the emissions whereas in this study estimates were obtained by using emission factors and amount of fuel used. The FTIR technique used by Bertchi *et al.* (2000) is often used to calculate emission factors such as those used in this study. The large discrepancies between this study and Bertchi *et al.'s* (2000) study is very interesting and may have to be investigated further as it suggest there is a large difference between measured and estimated values. There are several possible reasons for the differences between the two studies. One has to consider where the emissions were taken from, as the estimated values in this study are from households spread across the country, not just around Lusaka, thus giving a more average value.

It may be the population numbers used for scaling up as Bertchi *et al*. (2000) do not indicate whether rural or total population numbers were used. Another discrepancy is that this study incorporated emissions from charcoal as well as wood. The two different studies do, however, indicate that there is a lot of within country variation, thus showing the importance of increasing the sample size.

5.5 Comparison between biofuel combustion and savanna burning

Biofuel burning emissions from this study were low (except CH_4) compared to emissions from savanna burning in 1989 (table 5.4). A major reason for this is that fires in savannas are especially prevalent on the African continent, accounting for about half of the total biomass burned worldwide (Ward *et al.,* 1996). CH_4 from savanna burning is much lower than that produced from biofuel burning (table 5.4). Zambia contributed highest emissions from savanna burning and Namibia the least and this is due mainly to the difference in vegetation cover in these two countries.

Table 5.4: Emissions from savanna burning (Scholes *et al.*, 1996) and biofuel burning in southern Africa.

Country	Emission estimate					
	CO_2 (Tg yr^{-1})		CO (Tg yr^{-1})		CH_4 (Gg yr^{-1})	
	Biofuel	Savanna	Biofuel	Savanna	Biofuel	Savanna
Botswana	9.12	13.2	0.89	0.43	30.25	0.01
Malawi	3.15	7.1	0.32	0.24	10.36	0.00
Mozambique	2.64	25.6	0.22	1.03	13.97	0.03
Namibia	4.42	4.4	0.42	0.13	14.73	0.00
RSA	2.57	11.4	0.27	0.4	8.35	0.01
Zambia	0.88	53.6	0.08	2.50	2.94	0.08
Zimbabwe	0.25	7.2	0.02	0.26	0.83	0.08
Total	*23.03*	*122.5*	*2.22*	*4.99*	*81.43*	*0.16*

5.6 Contribution of biofuel use to global trace gas emissions

Southern Africa contributes a total of 23.03 Tg yr^{-1} of CO_2 emissions to the global biofuel burning estimate. This number is relatively small compared to other developing countries. For example, Brazil in Latin America is estimated to contribute a total of 65 Tg CO_2 per year (Yevich and Logan, 2003). Bangladesh in Asia contributes a total of 40.03 Gg NO, while China contributes 714.3 Gg NO per year to the global budget (Yevich and Logan, 2003), which is significantly higher than the emissions from southern Africa (29.4 Gg NO annually). The estimated annual values for biofuel emissions in southern Africa therefore suggest that compared to other developing countries southern Africa's contribution is relatively small, however emissions are still large compared to developed countries. Therefore it is still an important component of the global biofuel emissions calculation.

Chapter 6

Conclusions and recommendations

6.1 Conclusions

Trace gas emissions from domestic burning were investigated over the southern African region over an eight month period. Fuel types that were used in the region were wood, charcoal and maize residues. Wood was the preferred fuel in all southern African countries, with all households using wood as a major biofuel type. As a supplementary fuel charcoal was used in three countries (RSA, Mozambique and Zambia), while maize residue was used in one (Malawi).

Emissions were shown to vary significantly between months and there was no clear seasonal variation in any of the countries. In countries where only one fuel type was used, such as Zimbabwe, Namibia and Botswana, monthly variation was low; however in countries where several fuel types were used monthly emission variations increased significantly, particularly in Malawi where agricultural waste was burnt, these variations were due to changes in emission ratios of compounds for the different fuel types. Consumption rate is the major controlling factor of emissions and the lack of seasonal variation indicates that other factors beside seasonal changes control biofuel consumption and emissions. These findings are important for regional emission modeling as most models would include a seasonal variation based on temperature or biomass, however this data suggests that it is probably more appropriate to obtain an average annual value and apply this year round. Alternatively one has to obtain a better understanding of the other possible controlling factors.

Annual emissions in the region showed that RSA produced the most emissions from biofuels and Botswana the least. Emissions follow a similar trend to that of biofuel consumption rate, with rural population numbers also playing an influencing role over country emissions. The data shows some improvements on previous estimates, with CO_2 and CO emissions being higher and CH_4 emissions being lower than previous estimates. These changes are mainly due to the improved consumption rate data obtained for the region, as previously consumption rates from one country were applied to all countries in the region. The improved consumption data for each country highlights the variation in consumption and emissions from country to country. It is, therefore, just as important to devote time to improving consumption data across a region as it is to obtain reliable emission factors.

6.2 Recommendation for further research

During the course of this study other aspects that could be investigated in future to improve this data set even further were brought to the fore and these are discussed below.

- The use of biofuel burning in urban areas needs to be determined and added to the rural biofuel use to obtain a complete picture of biofuel use in each country.
- Charcoal production in some southern African countries is quite a large business and must lead to increased emissions. Determining the quantity of wood used and the emissions produced from this industry would also improve regional emission estimates.
- It may be useful to investigate land use in each country and determine whether there is any relationship with the types of fuel being used as these types of relationships are useful for future modeling. If there is a decline in the land areas where fuel is obtained from is there a decline in consumption rates? These are interesting topics which may require longer term studies.
- Finally, it would be appropriate to use this improved data set in other models or other settings to determine the social, economic and environmental impacts of domestic biofuel burning emissions on the region.

Appendix A:

Questionnaire where data was recorded in all months for data recording over the region.

	Breakfast					Lunch					Dinner				
Date	W	C	M	Kg	NO.	W	C	M	Kg	NO.	W	C	M	Kg	NO.

Where: W: Wood

C: Charcoal

M: Maize

Kg: Kilogram

NO.: Number of people

Appendix B:

Interviews were undertaken in all sites over the region. People who interviewed were those responsible for recording the data. Silas Mulaudzi and Phillip Tshikalanke undertook the interviews. Each household member was asked variety of questions that are listed below.

- What is your favourite fuel type and why?
- Do you buy fuel or you collect them free of charge?
- Do you collect them around or far away from your village?
- Do you use biofuel in all sessions (breakfast, lunch and dinner)? If not, why?
- Do you use anything else as a source of domestic energy beside biofuel? If yes, which one?
- What is the harvest period of maize residues, if you use it

Appendix C

Table indicates sites names, coordinates and altitude over the region.

Site	Coordinates (latitude)	Coordinates (longitude)	Altitude
Bobole	32.06	-25.06	33
Save	34.06	-21.06	58
Inhangoma	33.09	-16.01	368
Chamasoa	35.01	-15.09	1129
Kathewela	33.04	-13	1082
Nyungwe	34.01	-10.02	520
Kalomo	26.01	-17.03	296
Kapiri	28.08	-13.08	1261
Isoka	32.07	-9.07	1226
Chapfuce	30.01	-22	618
Masvingo	30.07	-19.07	1258
Goromonzi	31.04	-17.06	1250
Karasburg	18.07	-28	1007
Rehoboth	17.01	-23.03	1397
Tsaxara	16.06	-20.04	1624
Khakhea	23.05	-24.06	1048
Mokobaxane	24.09	-21.02	1670
Tsau	22.04	-20.01	941
Middleburg	25	-31.05	1253
Kroonstad	27.02	-27.06	1132

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